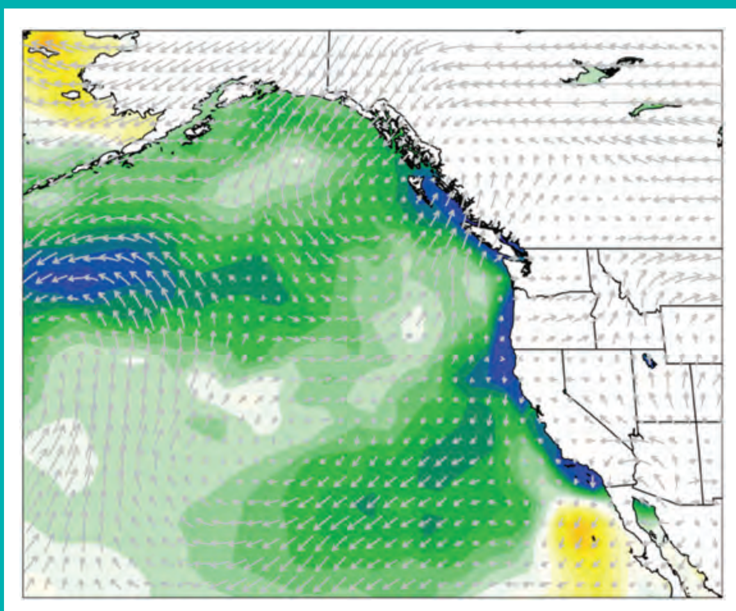
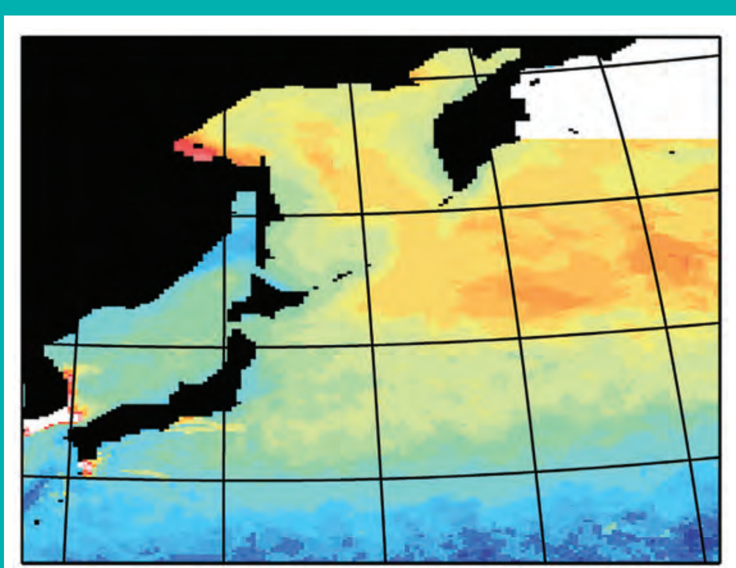
ISBN 1-897176-76-7
ISSN 1198-273X

PICES SCIENTIFIC REPORT
No. 40, 2011





Report of Working Group 20 on Evaluations of Climate Change Projections

NORTH PACIFIC MARINE SCIENCE ORGANIZATION

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This report was developed under the guidance of the PICES Science Board and its Physical Oceanography and Climate Committee. The views expressed in this report are those of participating scientists under their responsibilities.

This document should be cited as follows:

Foreman, M.G. and Yamanaka, Y. (Eds.) 2011. Report of Working Group 20 on Evaluations of Climate Change Projections. PICES Sci. Rep. No. 40, 165 pp.

PICES Scientific Report No. 40
2011

Report of Working Group 20 on Evaluations of Climate Change Projections

Edited by
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December 2011
Secretariat / Publisher
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Contents

1 Introduction

PICES Working Group on *Evaluations of Climate Change Predictions* (WG 20) was established in October 2005 at the PICES 2005 Annual Meeting in Vladivostok, Russia. As previous climate studies within PICES had generally been retrospective, it was felt that the upcoming 2007 release of the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), and the global climate model (GCM) projections associated with it, could provide a credible set of forecasts for forward-looking ecosystem studies in the North Pacific. Accordingly, the motivation for creating the Working Group was to evaluate these IPCC projections and, where possible, downscale them to sufficiently fine spatial scales so that they would be useful for continental shelf and coastal ecosystem studies. Though WG 20 was originally assigned a 3-year term, this was extended to 4 years at the PICES 2009 Annual Meeting in order to allow collaborations with the newly created PICES/ICES Working Group on *Climate Change Impacts on Fish and Shellfish*. The Physical Oceanography and Climate (POC) Committee was the only parent committee of WG 20, and the Co-Chairmen of the Working Group were Michael Foreman and Yasuhiro Yamanaka. The Terms of Reference (TORs) and the membership of the Working Group can be found in Appendices 1 and 2.

This report includes:

- an executive summary which briefly outlines the achievements of the Working Group as applied to the TORs, and provides recommendations for future follow-up activities within PICES;
- nine sections describing specific activities of WG 20 members (and colleagues) directed at one or more of the TORs; the reports are arranged by PICES member country;
- the working history of the Group (Appendix 5) and featured articles in PICES Press issues (Appendix 6).

2 Executive Summary and Recommendations

2.1 Summary of WG 20 Activities against Each of the Terms of Reference

1. *Analyse and evaluate climate change projections for the North Pacific and its marginal seas based on predictions from the latest global and regional models submitted to the Intergovernmental Panel on Climate Change (IPCC) for their 4th Assessment Report.*
   - Using results from the Canadian Earth System Model (Arora *et al.*, 2009; Christian *et al.*, 2010), Christian showed that in the 21st century the North Pacific will experience serious shoaling of the calcite and aragonite saturation horizons, with a variety of poorly understood biological impacts, and that the North Pacific will play a smaller role in the global ocean CO_2 sink than in earlier centuries. See section 3.1 for further details.
   - Merryfield *et al*. (2009) evaluated and examined future projections of global climate model (GCM) winds along the British Columbia continental shelf. See section 3.2 for more details.
   - Hashioka and Yamanaka (2007) and Hashioka *et al*. (2009) analysed marine ecosystem changes resulting from coupling the Japanese GCM MIROC (version 3.2) to lower and higher trophic level models for the Kuroshio-Oyashio system. See section 3.3 for more details.
   - Using simulations from GCMs submitted to the IPCC 4th Assessment Report, Jang *et al.* (2011) analysed and evaluated simulations and projections of the mixed layer depth (MLD) and its impact on primary production and timing of the spring bloom in the North Pacific Ocean. See section 3.4 for further details.
   - Yeh *et al.* (2009) examined MLD changes in the equatorial tropical Pacific Ocean and their relation with El Niño Southern Oscillation (ENSO) using the climate change projections from two IPCC GCMs. See section 3.4 for further details.
   - Curchitser *et al*. (this report) coupled a 10-km resolution Northeast Pacific Ocean circulation model to the NCAR CCSM GCM and demonstrated both local and global changes resulting from better resolved dynamics in the California Current System. See section 3.7 for more details.
   - Furtado *et al*. (2011) examined the major modes of North Pacific and tropical Pacific variability within GCMs used in the IPCC 4th Assessment Report. See section 3.8 for more details.
   - Overland and Wang (2007) and Wang *et al*. (2010) evaluated GCMs for their fidelity in reproducing the Pacific Decadal Oscillation and then used a subset of models for examining future changes in North Pacific sea surface temperature (SST). See section 3.9 for more details.
   - Wang and Overland (2009) evaluated GCMs for their accuracy in reproducing Arctic sea ice extent. See section 3.9 for more details.
   - Wang and Overland (this report) illustrated the assessment and culling of GCM projections with an example for SST and sea ice extent in the Bering Sea. See section 3.9 for further details.

2. *Facilitate analyses of climate effects on marine ecosystems and ecosystem feedbacks to climate by, for example computing an ensemble of the IPCC model projections for the North Pacific and making these projections available to other PICES groups such as CFAME.*
   - WG 20 members collaborated with the PICES Climate Forcing and Marine Ecosystem Task Team (CFAME) by:
     - Organizing joint workshops at three PICES Annual Meetings (2007–2009) and attending the CFAME workshop on "*Linking and visualizing climate-forcing mechanisms and marine ecosystem changes: A comparative approach*" (April 2008, Honolulu, U.S.A.);
     - Co-authoring King *et al.* (2011).

- WG 20 members collaborated with PICES/ICES Working Group on *Climate Change Impacts on Fish and Shellfish* (WGCCIFS) by:
  - Attending their meetings (Foreman and Yamanaka are WGCCIFS members);
  - Co-convening the session on "*Downscaling variables from global models*" at the International Symposium on *Climate change effects on fish and fisheries* (April 2010, Sendai, Japan);
  - Co-authoring papers with other members from the PICES community, for example, Ito *et al.* (2011).
- Di Lorenzo *et al*. (2008) showed strong correlations between the North Pacific Gyre Oscillation (NPGO) and salinity, NO_3, and Chl-*a* in the California Current; and salinity and NO_3 along Line-P.
- Di Lorenzo *et al*. (2010) showed that the low-frequency nature of the NPGO decadal climate mode originates from variability associated with the Central tropical Pacific Warming (CPW, a variation of ENSO) so that if projections of increased CPW frequency and magnitude are accurate (*e.g.*, Yeh *et al.*, 2009), then increased NPGO variance and a change in the background state of the North Pacific and its ecosystems can be expected.
- Hashioka and Yamanaka (2007) investigated the impacts the MIROC GCM climate projections on marine ecosystems in the Kuroshio-Oyashio system. See section 3.3 for more details.
- Navrotsky (this report) discussed both climate interactions on ecosystems, and ecosystem (especially phytoplankton) feedbacks to climate, from a general heat energy perspective. See section 3.5 for more details.
- Ustinova and Zuenko (this report) used possible climate projection scenarios to project marine ecosystem changes in the Far-Eastern Marginal Seas. See section 3.6 for more details.

3. *Facilitate the development of higher-resolution regional ocean and coupled atmosphere-ocean models that are forced by, and take their boundary conditions from, IPCC global or regional models.*

- North Pacific Regional Climate Models (RCMs) that have been developed, or are under development, by WG 20 members and colleagues are:
  - the California shelf (Auad *et al*., 2006);
  - the British Columbia shelf (Foreman *et al*.; see section 3.2 in this report);
  - the Northeast Pacific Ocean and Bering Sea (Curchitser *et al.*; see section 3.7 in this report). It is important to note that, as this model has two-way coupling to the NCAR GCM, it is the most advanced of all the RCMs;
  - the Washington–Oregon shelf (Bond, Curchitser, Hermann; under development).

4. *Facilitate the development of local and regional data sets (e.g., SST, river flow, sea ice cover) by incorporating information from climate model projections as well as observations and historical re-analyses.*

- Foreman *et al*. (2011) filled gaps in the last decade of winds measured at weather buoys along the British Columbia continental shelf and performed trend analyses over upwelling and downwelling periods. See section 3.2 for more details.
- Morrison *et al*. (2011) developed a method for estimating total freshwater discharge along the British Columbia coast and used it to reconstruct time series over the last 40 years. See section 3.2 for further details.
- Ustinova and Zuenko assembled various data sets (*e.g*., sea ice extent, SST, air temperature, sea level pressure) associated with Far-Eastern Marginal Seas and performed analyses of low-frequency climate variability. See section 3.6 for more details.
- Wang updates and maintains the website http://www.beringclimate.noaa.gov/ in which projections from culled IPCC models are published for the east Bering Sea region.

5. *Ensure effective two-way communication with CLIVAR;*

- CLIVAR representatives gave presentations at several WG 20/POC Annual Meetings;
- CLIVAR co-sponsored a workshop on "*Exploring the predictability and mechanisms of Pacific low frequency variability beyond inter-annual time scales*" at the PICES 2009 Annual Meeting (October, 2009, Jeju, Korea);

- Dr. Toshio Suga, member of the CLIVAR Pacific Panel, and a representative of CLIVAR at the PICES 2010 Annual Meeting (October 2010, Portland, U.S.A.), suggested co-sponsoring a topic session at the PICES 2012 Annual Meeting (October 2012, Hiroshima, Japan). He has also invited POC participation in the CLIVAR Pacific Panel meeting in April 2012;
- In addition, close relationships were established with the Ecosystem Studies in Sub-Arctic Seas (ESSAS) program. WG 20 members, Wang, Curchitser, and Foreman gave presentations at ESSAS annual meetings, and Christian was a plenary speaker at the ESSAS Open Science Meeting (May 2011, Seattle, U.S.A.).

6. *Convene workshops/sessions to evaluate and compare results;*

- WG 20 workshops and business meetings were held at each of the PICES Annual Meetings from 2006 to 2010. Three of these workshops meetings were held jointly with CFAME;
- a WG 20 member participated in the CFAME workshop on "*Linking and visualizing climate-forcing mechanisms and marine ecosystem changes: a comparative approach*" (April 2008, Honolulu, U.S.A.);
- a WG 20 member co-convened a session entitled "*Climate model projections*" at the International Symposium on the *Effects of climate change in the world's oceans* (May 2008, Gijón, Spain);
- a WG 20 member co-convened a session entitled "*Anthropogenic perturbations of the carbon cycle and their impacts in the North Pacific*" at the PICES 2009 Annual Meeting (October 2009, Jeju, Korea);
- a WG 20 member co-convened a session entitled "*Downscaling variables from global models*" at the International Symposium on *Climate change effects on fish and fisheries* (April 2010, Sendai, Japan).

7. *Publish a final report summarizing results*

- This is it!

2.2 Recommendations

1. The analysis and evaluation of IPCC global and regional climate model output (TOR #1) needs to be continued. The next IPCC release, Assessment Report 5, is scheduled for 2013, and some associated GCM output is expected by late 2011. James Overland, Muyin Wang, Chan Joo Jang, Sang-Wook Yeh and other PICES members are planning to evaluate these outputs. This activity may not warrant its own new working group but to keep abreast of the results of these analyses, PICES should ensure that it falls under the auspices of the Advisory Panels on Climate, Oceanographic Variability and Ecosystems (COVE) and/or Status, Outlooks, Forecasts, and Engagement (SOFE) of PICES' science program, FUTURE (**F**orecasting and **U**nderstanding **T**rends, **U**ncertainty and **R**esponses of the North Pacific **E**cosystem). Perhaps it could be a TOR under the expert group that is anticipated as a follow-up to WGCCIFS. (Note: Since the original submission of this report, a Section on *Climate Change Effects on Marine Ecosystems* was approved by PICES Science Board and Governing Council and was established in October 2011. See PICES website at http://www.pices.int/members/sections/CCME-S.aspx.)

2. A new working group to investigate North Pacific climate variability at time scales shorter (*e.g.*, interannual and decadal) than those that are the traditional focus of IPCC GCMs should be created. Past IPCC reports have focussed on century-scale projections, but IPCC Assessment Report 5 will also include decadal predictions. Though previous century-scale projections could only be evaluated statistically (*i.e.*, these projections did not predict conditions for specific future dates), the decadal predictions should be directly comparable with subsequent observations. The proposed new working group could contribute significantly to this IPCC activity and is an outcome of the workshop on "*Exploring the predictability and mechanisms of Pacific low frequency variability beyond inter-annual time scales*" that was convened by Emanuele Di Lorenzo and Shoshiro Minobe and held at the PICES 2009 Annual Meeting (October, 2009, Jeju, Korea). Draft TORs for this new working group (tentatively titled "North Pacific Climate Variability and Change") were presented at the 2010 Science Board meeting. The working group should be under the POC (and MONITOR?) committee(s), and already has the strong support of COVE-AP. (Note: Since the original submission of this report, this new working group was approved by PICES Science Board and Governing

Council and was established in June 2011. The final Terms of Reference for the Working group can be found in Appendix 3. Also see PICES website http://www.pices.int/members/working_groups/wg27.aspx.)

3. The development of RCMs around the North Pacific (TOR #3) will continue and to keep abreast of these developments, PICES should provide a venue for collaborative discussions among the developers. These RCMs will increasingly be coupled to more complex ecosystem models (*e.g.*, Yamanaka *et al*. in the Northwest Pacific, and Curchitser, Rose, Hermann *et al*. in the Northeast Pacific) and become increasingly valuable tools for FUTURE. Again, it is not clear where these activities best fit within PICES but they should fall under the auspices of some formal entity. Curchister *et al*. (this report) have not only demonstrated that important features (*e.g.*, upwelling) driving ecosystem states cannot be adequately discerned with GCMs, but have also shown that the feedback from resolving such features has impacts beyond the RCM domain. While these and other RCM results will be the subject of continued analysis and discussion, it is evident that RCMs are an essential tool for FUTURE, providing new information that cannot be gleaned from the statistical downscaling of GCM projections. (Note: Since the original submission of this report, a Working Group on *Regional Climate Modeling* was approved by PICES Science Board and Governing Council and was established in October 2011. For Terms of Reference for this Working Group, see Appendix 4. Also see PICES website http://www.pices.int/members/working_groups/wg29.aspx.)

4. Related to recommendation 3 above, live-access servers or ftp sites should be created to archive and provide easy access to results from North Pacific RCMs, analogous to the PCMDI archive for IPCC GCM results. This would be a natural follow-up to WG 20's TOR #4. Related observations and historical re-analyses could also be included on this site. The RCM output would provide fishery scientists with climate change variables on much finer spatial scales than can be resolved with the GCMs. This activity could be taken up by the COVE or SOFE Advisory Panels and/or the Technical Committee on Data Exchange (TCODE).

5. Links to GCM/RCM websites like the North American Regional Climate Change Assessment Program (NARCCAP, http://www.narccap.ucar.edu) should be provided (and regularly updated) through the PICES website. Similar links to useful GCM analyses and culling procedures, such as those described in section 3.9, should also be made easily available to the PICES community. "Guidance", or more accurately, suggestions, for model culling procedures have been summarized in Overland *et al.*, 2011.

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3 Activities of Working Group Members

3.1 The North Pacific Ocean in the enhanced greenhouse: Simulations with the Canadian Earth System Model, CanESM1

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Abstract

Ocean uptake of anthropogenic CO_2 has historically mitigated CO_2 emissions, but the ocean's capacity to absorb anthropogenic CO_2 may be declining due to climate change and ocean acidification. In the North Pacific, the zonal extent of the ocean basin decreases with increasing latitude, and the area of the subarctic zone may contract as warming moves the circumglobal wind patterns poleward. A set of historical and IPCC emission scenario runs were conducted with a coupled climate/carbon cycle model, the Canadian Earth System Model (CanESM1), to assess the effect of anthropogenic CO_2 forcing on the carbon cycle of the North Pacific in the 20th and 21st centuries. The model projects large increases in sea surface temperature globally, declining mixed layer depth and export production, and enhanced dinitrogen fixation. Trends in the North Pacific are generally coherent with global trends but in some cases are of opposite sign in the subtropical and subarctic regions. The subarctic zone, which accounts for the largest amount of CO_2 uptake, is getting smaller. The North Pacific share of global extratropical ocean CO_2 uptake is projected to decline from >50% in the preindustrial state to about 25% by 2100. The calcite and aragonite saturation horizons are projected to shoal significantly. Globally, the area where the saturation horizon is less than 200 m will more than double, including large areas of the northern North Pacific.

Introduction

Ocean uptake of anthropogenic CO_2 has given humans a significant subsidy in terms of climate change. Were 100% of CO_2 emissions to remain in the atmosphere, climate change would proceed much more rapidly. More than half of historic emissions are now dissolved in the world's oceans (Sabine *et al.*, 2004). As atmospheric CO_2 grows and begins to affect ocean temperature, stratification, circulation, and biology in increasingly significant ways, the fraction of new emissions taken up by the ocean on societally relevant time scales cannot be assumed to be the same as it was in the 19th and 20th centuries. In general, it should be expected to decline, causing a positive feedback on future warming (Denman *et al.*, 2007). Ocean ecosystems are also increasingly impacted by acidification caused by anthropogenic CO_2, and the North Pacific is particularly vulnerable because the lysocline is naturally shallow (Feely *et al.*, 2004).

A signature of anthropogenic climate change is the poleward migration of the circumglobal wind patterns that divide the midlatitude ocean into subtropical and subpolar gyres. This trend is better constrained (*e.g.*, more consistent across models) in the southern hemisphere than the northern, but is expected to occur in both hemispheres (Yin, 2005; Fyfe *et al.*, 2007). The subarctic Pacific is particularly vulnerable to these changes because the zonal extent of the basin decreases with increasing latitude. Hence the most biologically productive (subpolar) regions are shrinking. The biogeochemical effects of these changes are impossible to predict in detail, but there is some emerging consensus regarding the broad outlines (*e.g.*, Orr *et al.*, 2005). In this report an Earth System Model with prognostic land and ocean carbon cycle models and freely evolving atmospheric CO_2 concentration was used to assess the changes in ocean biogeochemistry resulting from CO_2 emissions and associated climate change, with emphasis on the North Pacific Ocean.

Methods

Model description

The model used is the Canadian Earth System Model v.1, which has been described at length in previous publications (Zahariev *et al.*, 2008; Arora *et al.*, 2009; Christian *et al.*, 2010). Its main features are summarized only briefly here. The atmosphere model is run at T47 spectral resolution, a 96 × 48 surface grid. The 192 × 96 ocean model, with four grid cells beneath each atmosphere grid cell, has a longitude/latitude resolution of approximately 1.875°. The ocean carbon cycle model is based on the Ocean Carbon Cycle Model (OCMIP II) protocols (Najjar and Orr, 1998) and couples the carbon cycle to an NPZD (nutrient phytoplankton zooplankton detritus) ecosystem model via a fixed C/N Redfield Ratio and a temperature-dependent rain ratio (ratio of inorganic to organic carbon in vertical flux at the base of the euphotic zone) (Zahariev *et al.*, 2008). The terrestrial carbon cycle uses the atmosphere grid and the Canadian Land Surface Scheme (CLASS) v. 2.7. It includes “downregulation” of photosynthesis under a high-CO_2 atmosphere, as described by Arora *et al.* (2009) and historic land-use change, as described by Wang *et al.* (2006). Atmospheric CO_2 is freely varying and inert (no sources or sinks within the atmosphere).

Atmospheric CO_2 is carried as a three-dimensional advected tracer, and treated as such in the radiation calculations. Other major greenhouse gases such as CH_4 and N_2O are assumed to be spatially uniform and are treated individually in the radiation code. A small adjustment to the radiative transfer scheme was made subsequent to the simulations described in the publications cited above, to reduce the climate sensitivity to non-CO_2 greenhouse gases. Concentrations and emissions are from the Special Report on Emissions Scenarios (SRES) A2 scenario (IPCC, 2000). This is a “high emission” scenario, where atmospheric CO_2 concentration continues to grow exponentially throughout the 21st century, exceeding 800 ppm by 2100. For CO_2, only emissions are used while for CH_4 and N_2O, the atmospheric concentrations are specified according to the scenarios. The model does an excellent job of reproducing the observed historical atmospheric CO_2 concentrations when forced with historic emissions (Arora *et al.*, 2009). All other forcings (*e.g.*, solar and aerosol) are fixed at 1850 values and are as described in Arora *et al.* (2009) and Christian *et al.* (2010).

Results

Global mean trends

Global mean trends in ocean biogeochemical fields show substantial alteration in the 21st century which, in many cases, is well underway by the end of the 20th (Fig. 3.1.1). Mixed layer depth declines by ~3 m by 2000 and 10 m by 2100 (Fig. 3.1.1). This is principally a result of less deep convection in the high latitudes, as the model vertical resolution is inadequate to meaningfully simulate the variability of the low-latitude mixed layer; the model simulates the global distribution of maximal winter mixing depth well (Zahariev *et al.*, 2008). Export production and dinitrogen (N_2) fixation also show more or less monotonic trends that are well underway by 2000 (Fig. 3.1.1). Some biogeochemical fields, such as primary production and $CaCO_3$ export, do not show monotonic trends (Fig. 3.1.1), but show competing effects of declining productivity due to increasing stratification and enhancement under a warming climate because N_2 fixation and the rain ratio are parameterized as functions of temperature. This illustrates the indirect effects that make detection particularly difficult. Ocean CO_2 uptake continues to increase, but the rate of growth declines towards the second half of the 20th century (Fig. 3.1.1).

Regional trends relative to global trends

The correlation of local or regional trends with global trends is given in Table 3.1.1 for some of the fields shown in Figure 3.1.1. pH and surface ocean $p$$CO_2$ and dissolved inorganic carbon (DIC) were excluded because these trends are quite uniform globally, so that all of the correlation coefficients exceed 0.97. The benchmark North Pacific stations HOT (Station ALOHA), KNOT, and PAPA (OSP) are illustrated along with HOT’s subtropical Atlantic sister-station BATS, and regional means for the North Pacific and North Atlantic. Sea surface temperature shows a global trend nearly as uniform as $p$$CO_2$ and DIC, with the weakest correlation of 0.90 at OSP (Table 3.1.1). Sea surface salinity, by contrast, shows regional variations, with a general trend towards greater salinity in the subtropics (*e.g.*, BATS) and freshening in the subarctic Pacific. Mixing depth does not show coherent patterns at individual stations but the regional trends are strongly correlated with the global trend. The same is true of ocean CO_2 uptake. The subtropical stations are more coherent with the global and regional trends than with the subarctic ones. At the subarctic stations, CO_2 uptake declines due to reduced export production, warmer temperatures, and weaker vertical mixing in winter while at the subtropical ones, increased dinitrogen fixation (DNF) counteracts these trends (which would have less effect in any case because the environment is already warm, stratified, and oligotrophic). DNF shows strong positive correlations across the board because the subtropical environment that HOT and BATS represent dominates the global and regional trends. Primary and export production declines globally, with the counter-trend in the subtropics, again, driven by DNF. Export production in CanESM1 is dominated by the Southern Ocean (Zahariev *et al.*, 2008), but the decline in the 21st century is primarily in the northern hemisphere mid-latitudes (not shown). $CaCO_3$ export shows little temporal trend globally (Fig. 3.1.1) and little correlation of regional and global trends (Table 3.1.1).

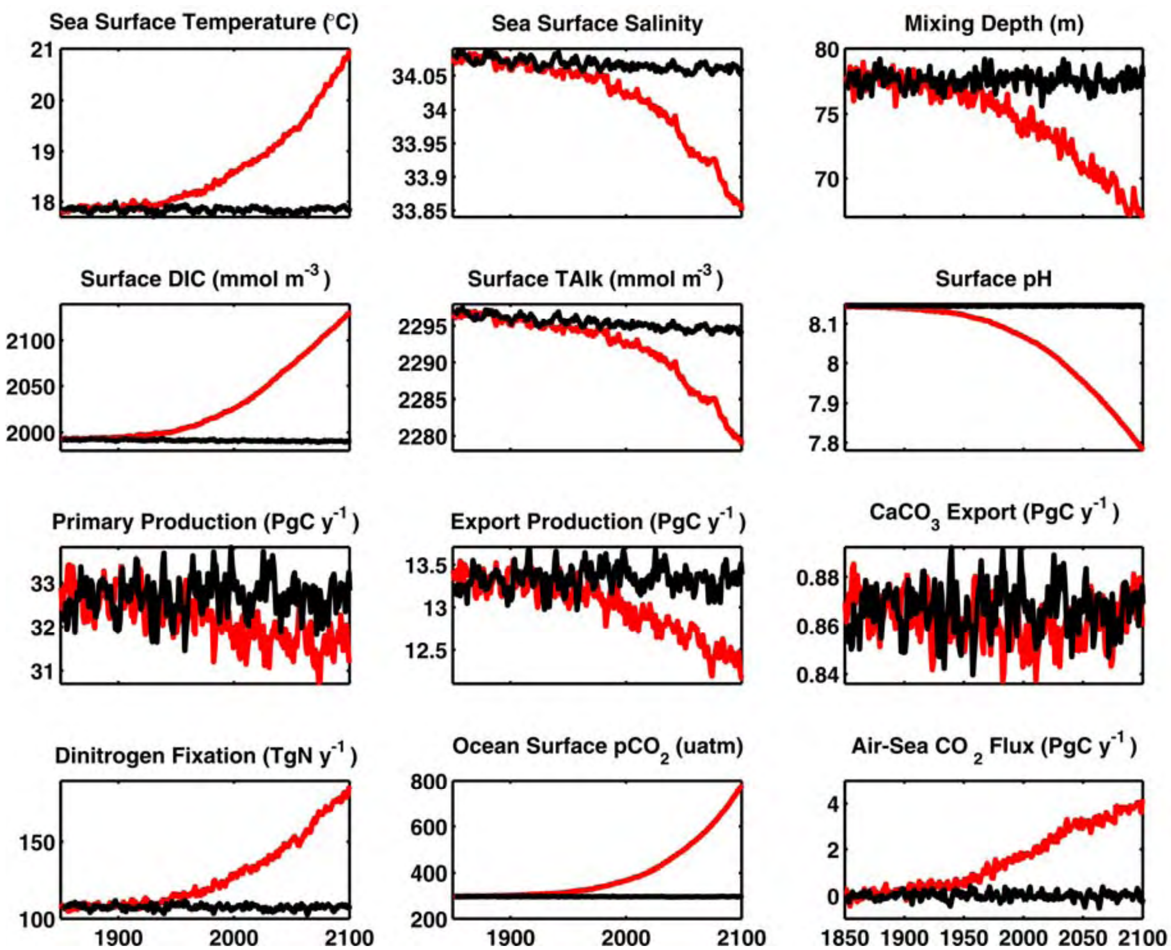

Fig. 3.1.1 Global mean or integral ocean properties for 1850–2100 under the SRES A2 scenario.

Table 3.1.1 Correlation coefficients for region or station *vs* global means/integrals of ocean properties for 1850–2100. pH and surface pCO_2 and DIC were excluded because correlation coefficients exceed 0.97 in all cases. Dinitrogen fixation does not occur at OSP or KNOT.

	NPAC	NATL	BATS	HOT	OSP	KNOT
Sea surface temperature	1.00	0.99	0.98	0.96	0.90	0.94
Sea surface salinity	0.94	–0.24	–0.93	–0.24	0.77	0.52
Mixing depth	0.78	0.87	0.23	0.31	0.44	–0.55
Surface alkalinity	0.96	0.16	–0.93	0.02	0.85	0.64
Primary production	0.33	0.59	–0.61	–0.73	0.24	0.19
Export production	0.49	0.83	–0.84	–0.93	0.37	0.42
$CaCO_3$ export	–0.12	–0.12	–0.02	–0.16	–0.15	0.01
Dinitrogen fixation	0.99	0.99	0.97	0.94	–	–
Air–sea CO_2 flux	0.96	0.95	0.85	0.70	0.41	–0.21

NPAC – North Pacific, NATL – North Atlantic

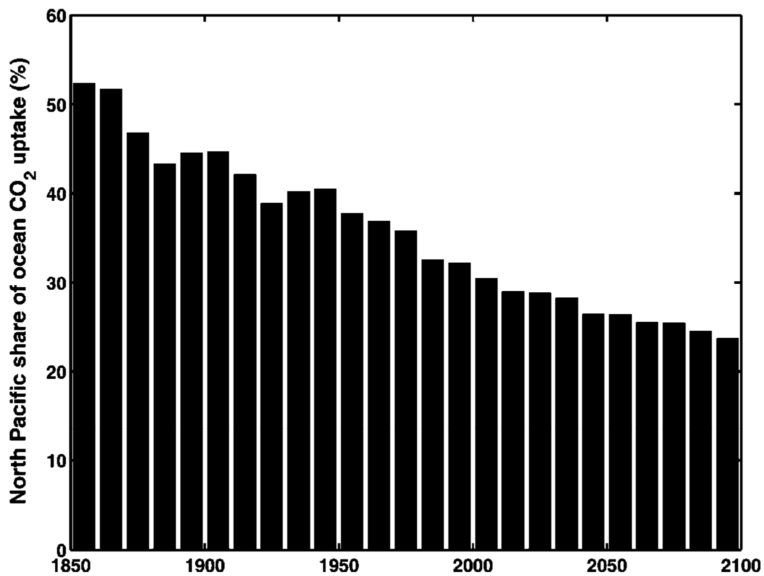

Fig. 3.1.2 North Pacific (20–65°N) fraction of global extratropical (>20°N) CO_2 uptake, for the A1B emissions scenario (means of 10 year periods from 1850–2100).

Ocean CO_2 uptake

Ocean uptake of anthropogenic CO_2 has helped to mitigate climate change, but climate change is itself beginning to alter ocean processes that affect rates of CO_2 uptake. It has mostly been assumed that ocean uptake of anthropogenic CO_2 (distinct from atmospheric CO_2 generally) is an abiotic process driven by rising atmospheric concentration, and that the biological component is small or negligible because the strength of the biological pump has changed little since the preindustrial state. In the North Pacific Ocean, modelled ocean uptake of CO_2 declines throughout the 21st century relative to the extratropical ocean as a whole (Fig. 3.1.2). (In general, the tropical ocean is a source of atmospheric CO_2 and the extratropical ocean is a sink; it is not possible to calculate the ratio of a specific region to the global integral because the global total is zero in the preindustrial state.) All of the changing ocean processes discussed above contribute to this trend: greater stratification (shallower mixing depth), warmer sea surface temperature (decreased solubility of CO_2), and a weakening biological pump expressed as lower export production (Fig. 3.1.1 and Table 3.1.1). As noted above, the latter trend is counteracted in the subtropical ocean by increasing dinitrogen fixation, but in the North Pacific, the contribution of this process is relatively small and the region declines in importance as a CO_2 sink. This is likely because the subtropical region (weak CO_2 sink) is expanding poleward at the expense of the subarctic (strong sink), whose total area is contracting due to the basin geometry.

Ocean acidification

The North Pacific is among the regions most vulnerable to the calcium carbonate undersaturation impact of anthropogenic CO_2 because the saturation horizon is naturally shallow (Fig. 3.1.3). Accumulated anthropogenic CO_2 causes notable shoaling of the saturations horizons for aragonite (ASH) and calcite (CSH), with the ASH rising above the 100 m level over large areas of the North Pacific by 2100 (Fig. 3.1.3).

The fraction of the total ocean area where the ASH lies at less than 200 m depth increases by about 20% from 1850–2000, and more than doubles relative to the preindustrial state by 2100 (Table 3.1.2). So the vast majority of the 1850–2100 increase occurs in the 21st century, but the trend is already well underway by 2000. The area where the CSH lies at less than 500 m depth increases only about 10% by 2000, but by two thirds (relative to preindustrial) by 2100 (Table 3.1.2).

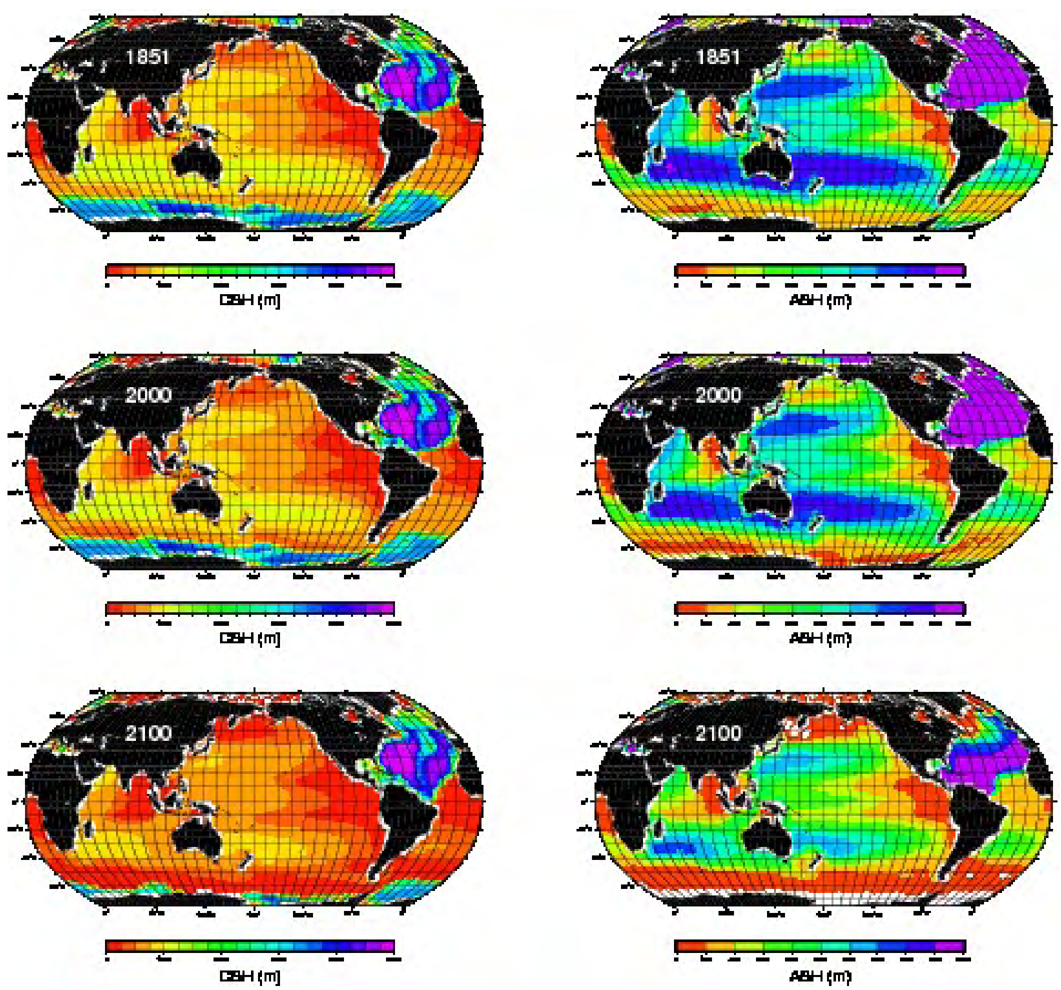

Fig. 3.1.3 Depth of calcite (CSH) and aragonite (ASH) saturation horizons for 1851, 2000, and 2100 under the SRES A2 scenario.

Table 3.1.2 Area of ocean in which the aragonite saturation horizon (ASH) is found at depths < 200 m or the calcite saturation horizon (CSH) at < 500 m (millions of square km); % PI indicates percentage of preindustrial (1850) value; % NP indicates North Pacific fraction of global total.

	ASH<200	% PI	% NP	CSH<500	% PI	% NP
1850	71.4		5.9	164		11.1
2000	85.3	119	7.1	182	111	11.4
2100	154	216	8.8	272	166	10.1

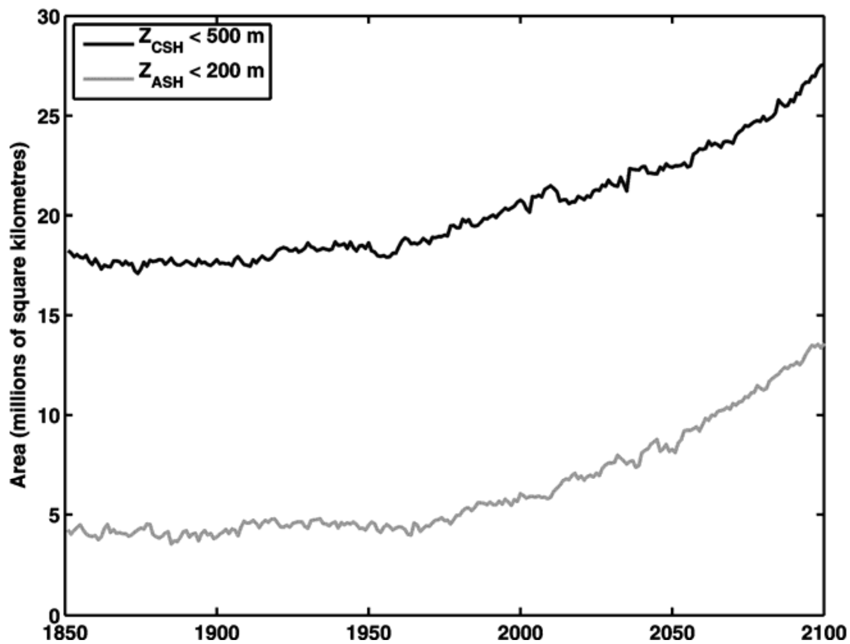

Fig. 3.1.4 Total area in the North Pacific Ocean (20–65°N), with the calcite saturation horizon (CSH) less than 500 m and the aragonite saturation horizon (ASH) less than 200 m, 1850–2100.

The North Pacific share of the global ocean area with a shallow lysocline increases quite rapidly for aragonite, but not for calcite (Table 3.1.2). In the North Pacific, the area with an aragonite saturation horizon depth (Z_{ASH}) less than 200 m is more than triple the preindustrial value by 2100 (Fig. 3.1.4), and the North Pacific share of the global ocean area with Z_{ASH} < 200 m increases by half, from about 6 to 9% (Table 3.1.2). The North Pacific share of the area where the calcite lysocline (Z_{CSH}) is less than 500 m is relatively constant at 10–11% (Table 3.1.2), and peaks in about 2050, declining thereafter as larger areas with Z_{CSH} < 500 m develop in the tropics and the Southern Ocean (not shown). Nonetheless, the total area with Z_{CSH} < 500 m in the North Pacific increases by about half, from 18 to 28 million square kilometres (Fig. 3.1.4).

Discussion and Conclusions

The impacts of warming climate and ocean acidification are still very uncertain, and model projections are, at best, hypotheses. Ocean acidification due to accumulation of anthropogenic CO_2 is a robust prediction (Orr *et al.*, 2005), but its biological impacts and feedbacks are still largely unknown (and are not considered in this version of the model). The model projects declining export globally, a potential positive feedback on atmospheric CO_2 growth, but this trend is counteracted by increasing dinitrogen fixation. In the model, both dinitrogen fixation and the inorganic/organic carbon flux "rain ratio" are parameterized as increasing with increasing sea surface temperature. These parameterizations are based more on the apparent latitudinal distribution of these processes in the modern ocean than on any well constrained statistical relationship with temperature *per se*. While it is certainly plausible that the subtropical gyre will expand poleward at the expense of the subarctic region, it is less certain that dinitrogen fixation within the subtropical region will continue to increase with rising surface temperature as it does in the model (which does not consider, *e.g.*, supplies of iron and phosphorus as potentially limiting factors). Nonetheless, it seems clear that the North Pacific in the 21st century enhanced greenhouse will experience serious shoaling of the calcite and aragonite saturation horizons, with a variety of poorly understood biological impacts, and that the North Pacific will play a smaller role in the global ocean CO_2 sink than in earlier centuries. Improved parameterizations of dinitrogen fixation, calcification, and calcite and aragonite dissolution will help to elucidate the regional details of these trends.

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3.2 Climate trends and projections along the British Columbia continental shelf

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Summary

PICES Working Group 20 research in British Columbia (BC) waters focused on contributions to each of the first four Terms of Reference. Specifically, they were directed at:

- analysing and evaluating historical simulations and projections of winds along the BC shelf using results from global climate models (GCMs) submitted to the Intergovernmental Panel on Climate Change (IPCC) for their 4th Assessment Report. The results of this analysis were published in Merryfield *et al*. (2009) and are summarized in section I.
- facilitating analyses of climate change effects on marine ecosystems and ecosystem feedbacks by participating in workshops organized jointly with the Climate Forcing and Marine Ecosystems (CFAME) Task Team, and contributing to a paper (King *et al*., 2011) that estimated climate change impacts on the California Current ecosystem. In addition, Drs. Michael Foreman and Yasuhiro Yamanaka were members of the PICES/ICES Working Group on *Climate Change Impacts on Fish and Shellfish* (a successor to CFAME) and in that capacity, Dr. Foreman co-convened the session "*Downscaling variables from global models*" at the International Symposium on *Climate Change Effects on Fish and Fisheries* in Sendai, Japan, April 25–29, 2010.
- developing and running a high-resolution regional climate model for the BC continental shelf that is forced by, and takes its boundary conditions from, IPCC global and/or North American regional climate models. A progress report on this development is given in section II.
- augmenting the Faucher *et al*. (1999) extended data set of buoy wind measurements off the BC coast by filling gaps over the last decade with values from a NASA archive, and analysing the 50-year time series for trends in the upwelling and downwelling magnitudes and timing. This work is described in Foreman *et al*. (2011) and summarized in section III.

I Downscaling GCM Winds off the BC Shelf

As this section is largely a summary of Merryfield *et al*. (2009), the interested reader is referred to that publication for more details.

Surface marine winds along the west coast of Canada have a pronounced influence on the oceanography and ecosystems of the region. Although other forcing influences like tides, the bifurcation of the eastward North Pacific Current into the southward California Current and the northward Alaska Current, and freshwater forcing from coastal rivers also contribute, marine winds dominate the seasonality of the coastal surface currents. In autumn and winter, the Aleutian Low pressure system generally gives rise to southerly winds and a northward-flowing, downwelling coastal current regime. In the spring and summer, a relatively stable offshore high pressure system produces northwesterly winds and a southward flowing, upwelling regime. This seasonal cycle strongly modulates primary production and is a main reason why the continental shelf off southern Vancouver Island supports such a large fishery (Ware and Thomson, 2005).

Long-term observations of the coastal winds in this region have been made via a network of coastal meteorological buoys (Fig. 3.2.1) since the late 1980s (Cherniawsky and Crawford, 1996). Faucher *et al*. (1999) extended these time series back another 30 years with an empirical-statistical downscaling procedure that was applied to large-scale predictors derived from the National Centers for Environmental Prediction (NCEP) reanalysis. The resulting data set consists of 6-hourly winds at 13 buoy sites for the period 1958–1997. This data set provides an excellent basis for not only examining possible trends and shifts (section III), but also for evaluating the winds produced by global climate models. The aim of this study was to examine projected changes in surface marine winds off the Canadian west coast, under the assumption they should have significant impacts on coastal ecosystems. This was done by interpolating winds from 18 IPCC climate model simulations (Table 3.2.1) to the buoy locations and comparing contemporary and future decadal averages.

To facilitate our analyses, the buoys were grouped into four categories (Table 3.2.2). The first step in the analysis was to assess the accuracy of the model winds through comparisons with buoy observations. Figure 3.2.2 summarizes results for summer (June–August) over the 20-year period of 1976–1995 and shows that despite the coarse resolution of the CGMs, there is relatively good agreement between the models and observations. Though there is scatter among the models, their ensemble averages display reasonably accurate upwelling winds at the near offshore and inshore buoy locations.

Figure 3.2.3 summarizes GCM projected wind changes, shown as fractional increases in magnitude and directional changes (degrees clockwise) over the periods 2030–2049 and 2080–2099 relative to 1976–1995, at the near offshore buoys. The winter (January–March, JFM) winds show sufficient scatter among the GCMs so that no statistically significant pattern emerges, though the multi-model ensemble means suggest an approximately 5% intensification and slight counterclockwise rotation. However, a much clearer picture emerges for the summer (June–August, JJA) wind changes. Although only a few of the individual model changes are significant, the ensemble means exhibit wind speed increases of approximately 2–4% and clockwise rotations of about 2° that, in some instances, are statistically significant. The JJA wind changes between 1976–1995 and 2080–2099 show similar, though considerably stronger, trends consisting of wind speed increases ranging from 4.5 to 9% and clockwise rotations between 4° and 5°. The strength of this signal is reflected in substantial inter-model consistency, with 16 models showing clockwise rotations.

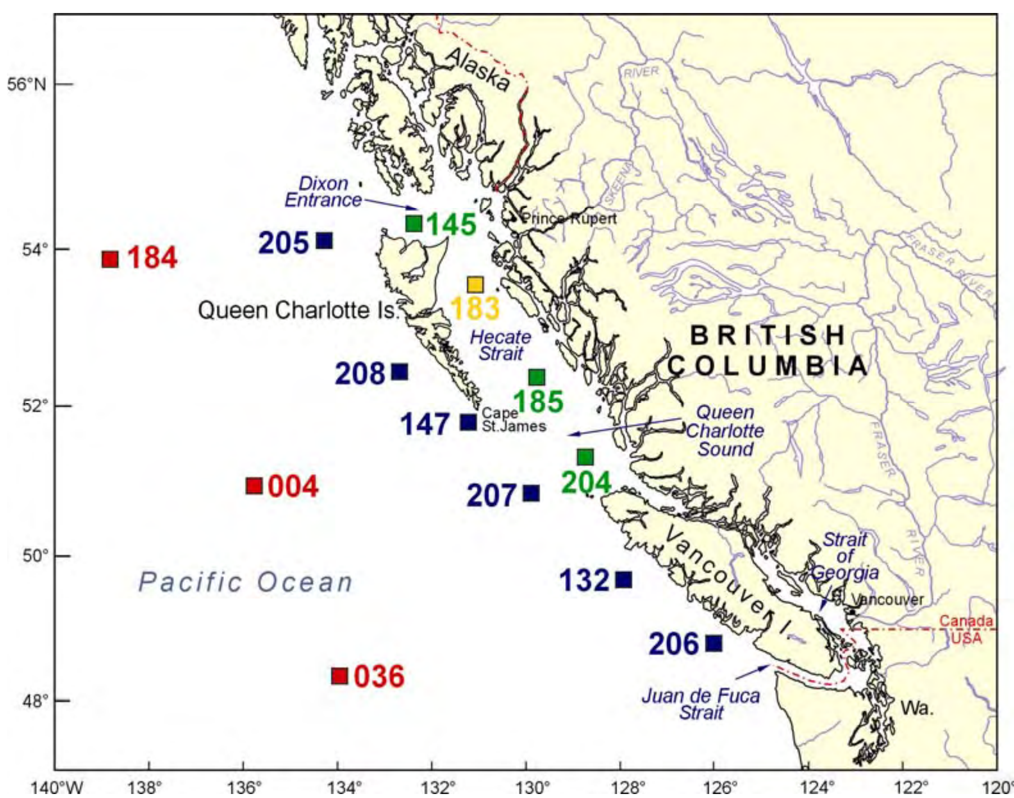

Fig. 3.2.1 Locations of 13 weather buoys off the Canadian west coast. Colours denote the four categories described in Table 3.2.2.

Table 3.2.1 Climate models used in this study and their atmospheric resolutions (from Merryfield *et al*., 2009).

Symbol	Institution/Model	Atmospheric resolution*	Horizontal grid dimensions, longitude × latitude
a	BCCR/BCM2.0	T63L31	128 × 64
b	CCCMA/CGCM3.1 (T47)	T47L31	96 × 48
c	CCCMA/CGCM3.1 (T63)	T63L31	128 × 64
d	CCSR/MIROC3.2 (med)	T42L20	128 × 64
e	CNRM/CM3	T63L45	128 × 64
f	CSIRO/Mk3.5	T63L18	192 × 96
g	GFDL/CM2.0	2.5° × 2°L24	144 × 90
h	GFDL/CM2.1	2.5° × 2°L24	144 × 90
i	GISS/AOM	4° × 3°L12	90 × 60
j	GISS/EH	5° × 4°L20	72 × 46
k	GISS/ER	5° × 4°L20	72 × 46
l	INM/CM3.0	5° × 4°L21	72 × 45
m	IPSL/CM4	2.5° × 3.75°L19	96 × 72
n	MIUB/ECHO-G	T30L19	96 × 48
o	MPI/ECHAM5	T63L31	192 × 96
p	MRI/CGCM2.3.2	T42L30	128 × 64
q	UKMO/HadCM3	3.75° × 2.5°L19	96 × 72
r	UKMO/HadGEM1	1.875° × 1.2.5°L38	192 × 144

* Horizontal resolution is described by spectral truncation or grid box dimensions as appropriate, and vertical resolution by the number of model levels, *e.g.*, L31.

Table 3.2.2 List of buoys and their positions (from Merryfield *et al.*, 2009).

Buoy	Lat.	Long.	Classification
004	50.93N	136.10W	Far offshore
036	48.35N	133.94W	Far offshore
132	49.74N	127.93W	Near offshore
145	54.37N	132.42W	Inshore
147	51.83N	131.22W	Near offshore
183	53.62N	131.10W	Hecate Strait
184	53.91N	138.85W	Far offshore
185	52.42N	129.79W	Inshore
204	51.37N	128.75W	Inshore

Table 3.2.2 Continued

Buoy	Lat.	Long.	Classification
205	54.16N	134.28W	Near offshore
206	48.84N	126.00W	Near offshore
207	50.87N	129.92W	Near offshore
208	52.52N	132.69W	Near offshore

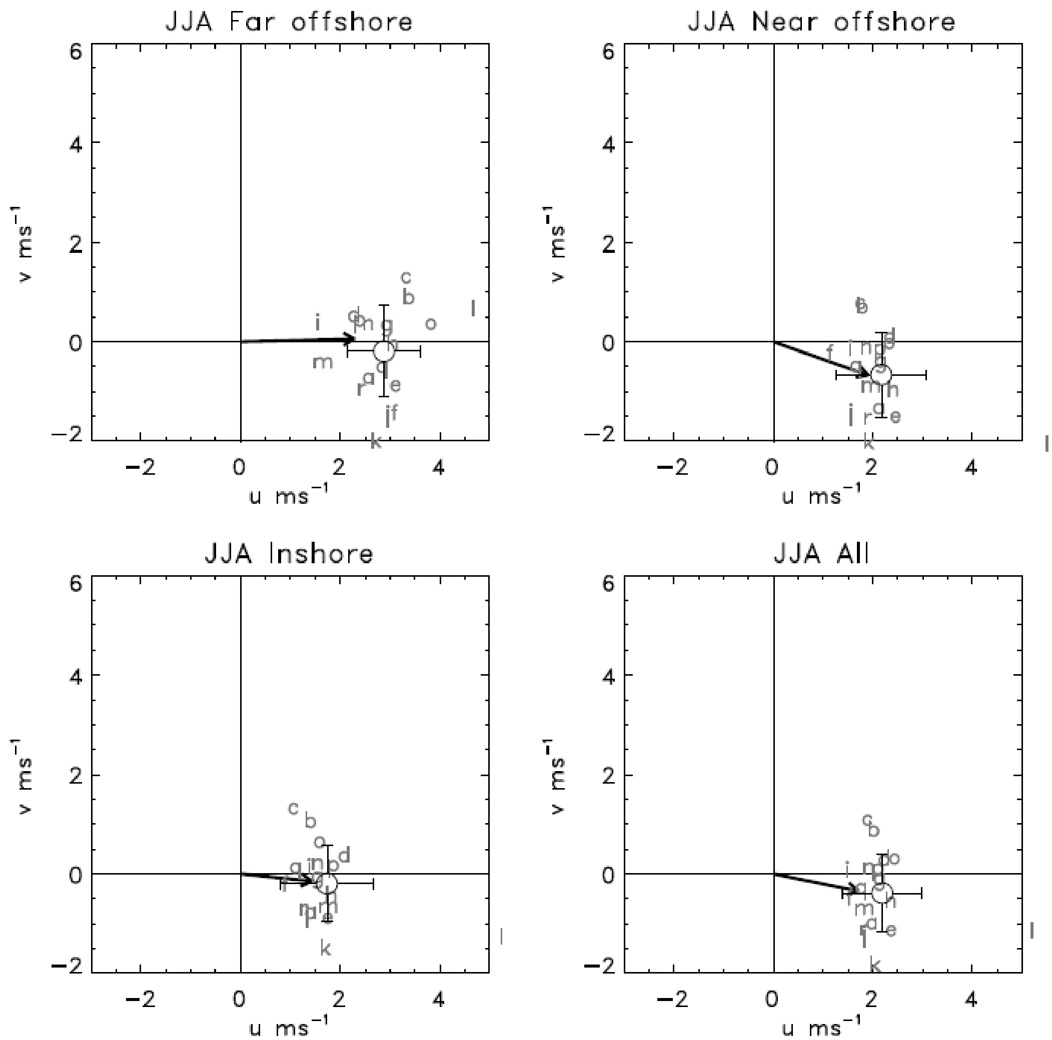

Fig. 3.2.2 Summer (June–August, JJA) 1976–1995 mean surface winds from buoy observations (vectors), individual GCMs (alphabetical codes from Table 3.2.1), and multi-model mean (large circles) for our regional groupings of the buoys (from Merryfield *et al*., 2009). Error bars represent standard deviations of the multi-model ensemble.

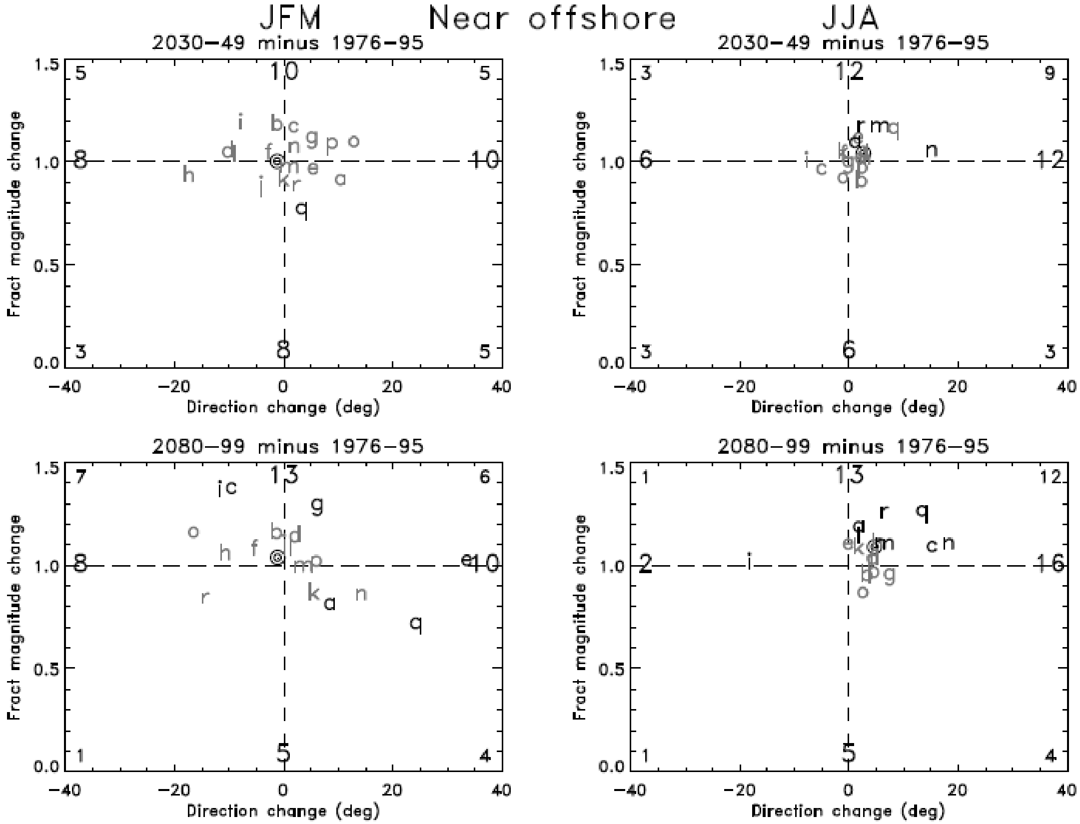

Fig. 3.2.3 Future changes in January–March (JFM, left) and June–August (JJA, right) surface winds, averaged at the near offshore buoy locations, between the 1976–1995 base period and 2030–2049 (upper panels) and 2080–2099 (lower panels) (from Merryfield *et al*., 2009). The letters correspond to individual models as in Table 3.2.1, and the bulls-eyes to multi-model means. The larger numerals indicate the numbers of models residing in the corresponding half planes, and the smaller numerals denote the number of models in the corresponding quadrants. Bold letters indicating a probability that such a result would arise under the null hypothesis of no change is less than 0.05.

Though the foregoing projected changes may have significant implications for marine ecosystems along the southern BC continental shelf where summer upwelling winds bring nutrients to the surface and drive upper trophic level productivity (Ware and Thomson, 2005), several other projected changes need to be considered before the complete picture is understood. Warmer air temperatures can be expected to heat the sea surface and contribute to a stronger stratification that will inhibit upwelling. Climate model analyses along the southern California shelf by Auad *et al*. (2006) showed that an increase in upwelling wind speed was sufficient to overcome stronger stratification. However, this result may not carry over to BC where water column stratification is largely determined by salinity rather than temperature variations. Projected changes in precipitation and river discharge (Morrison *et al*., 2002), as well as the air–sea heat flux, will thus be needed to force a regional coastal ocean model in order to provide better estimates of physical changes to the coastal waters off BC. The development of such a regional ocean-only climate model is described in the next section.

II Regional Climate Model Development for the BC Shelf: Progress to Date

The ocean model that will be used to estimate future circulation and water properties along the BC shelf was developed by Masson and Fine (2011). It is an application of the Regional Ocean Modeling System (ROMS, Haidvogel *et al*., 2008) with approximately 3 km resolution, and the coverage is shown in Figure 3.2.4. (Note that ROMS was also used in the Northeast Pacific simulations described in section 3.7 (Curchitser *et al*.)). The model is forced with tides, daily wind and heat flux from the North American

Regional Reanalysis (NARR), freshwater runoff, and salinities and temperatures that are nudged back to climatology along the lateral ocean boundaries. With initial temperatures and salinities taken from this same climatology, a model simulation over the period 1995–2009 has been shown to reproduce the major seasonal currents and elevation time series from coastal tide gauges with reasonable accuracy. The interested reader is directed to Masson and Fine (2011) for more details.

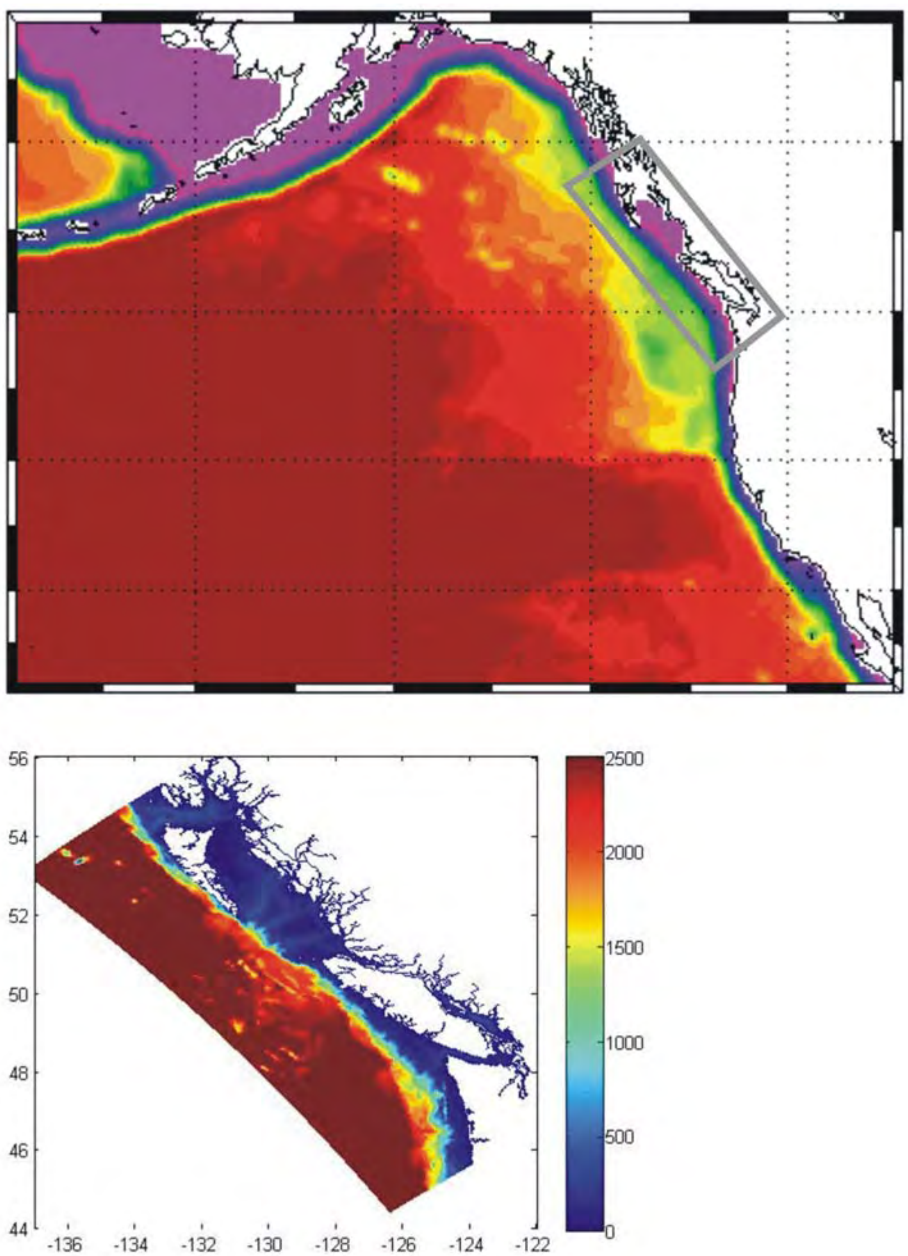

Fig 3.2.4 Coverage and bathymetry (m) for the British Columbia (BC) regional climate model.

In order to use this model for future projections, it need only be run with suitable future forcing and initial fields. As the gravitational forcing fields that determine the tides are completely predictable, that component can be easily forecast. The required atmospheric forcing can be obtained by applying downscaling techniques to output from GCMs and/or regional climate models (RCMs) that are available from either:

- the Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model data set of the World Climate Research Programme (WCRP), assembled at the Program for Climate Model Diagnosis and Intercomparison (PCMDI, http://www-pcmdi.llnl.gov/) to inform the IPCC 4th Assessment, or
- the North American Regional Climate Change Assessment Program (NARCCAP, http://www.narccap.ucar.edu/).

As the NARCCAP data has a finer horizontal resolution (approximately 50 km) and thus should be better to able to capture spatial variations in (1) terrestrial precipitation (both rainfall and snowfall) and (2) oceanic winds and heat fluxes, it was chosen. As a consequence, our model simulations focussed on the NARCCAP-defined "current" and "future" time periods of 1970–1999 and 2040–2069, respectively. Note that the NARCCAP future simulations assume the A2 emissions scenario (no leveling off of greenhouse gases). Initial conditions, boundary conditions and atmospheric forcing values were generally constructed for the future scenario by calculating anomalies between future and current scenarios from larger-scale models and adding them to the current scenario values.

There are 6 RCMs within NARCCAP. Though we eventually aim to force our BC shelf model with the atmospheric anomalies from all 6 and compute ensemble averages of the associated results, our initial anomalies for air temperature, air pressure and humidity were calculated using only one, the Canadian Regional Climate Model (CRCM) which, in turn, was forced by the Canadian Global Climate Model (CGCM3). Since the CRCM has significantly lower resolution than our oceanic shelf model, there were regions that it defined as land and our model defined as water. As the values for air temperature, air pressure and humidity given by the CRCM in these regions were affected by being over land, new values for these coastal areas were calculated using Empirical Orthogonal Functions (EOFs). These EOFs were generated using NARR data over a 15- year period between 1995 and 2009 where 14 years were used to generate the EOFs and the remaining year was used to test the ability of the EOFs to generate coastal data based on offshore data. Ten EOFs were used to approximate the data and the regeneration of the test year was accomplished with an average R-squared value of 0.95 and p-values with an order of magnitude 10^{-5}.

Dealing with the rest of the atmospheric forcing was less complex. As no land effects were noticeable in the CRCM precipitation output, these data were used as-is to calculate the necessary anomalies. Shortwave and longwave radiation showed no significant difference between the current and future scenarios, so these forcings were left at their current scenario values.

Anomalies for the initial oceanic temperature and salinity fields were calculated from CGCM3 output. As with the CRCM downscaling, the coarse CGCM3 resolution necessitated downscaling to the ROMS grid. However, in this case the number of points in the 3-D GCM grid would have made using EOFs prohibitive, so latitudinal average anomalies were found and applied to the current scenario fields over the entire grid. The results are shown in Figure 3.2.5. The same field was applied to the boundary temperature and salinity.

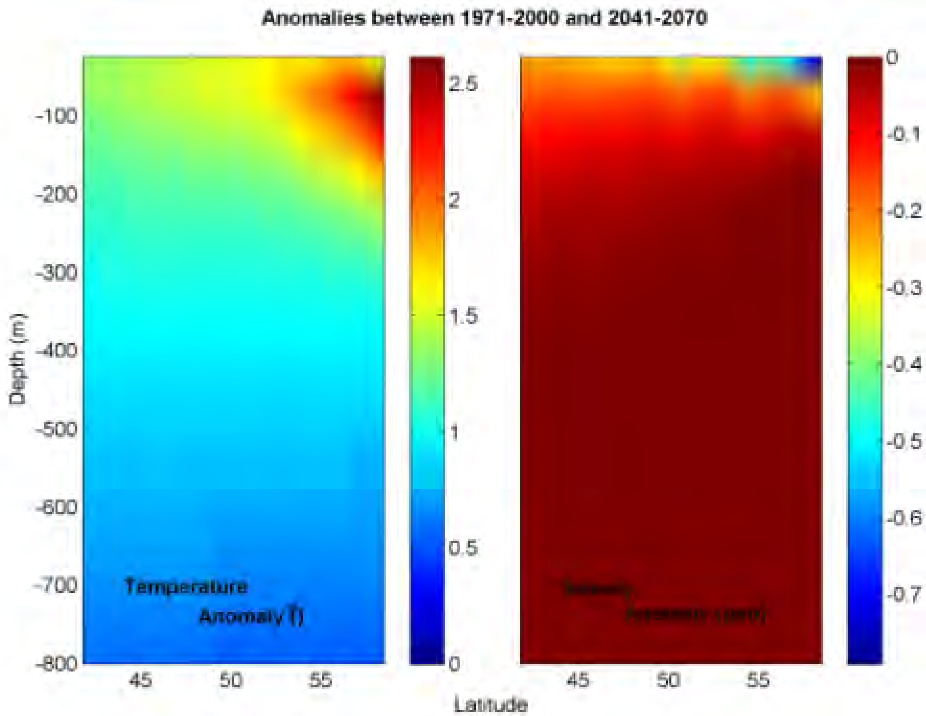

Fig. 3.2.5 Temperature and salinity anomalies as functions of latitude and depth, between 1971–2000 and 2041–2070, as computed from the CCCma CGCM3.1 T47 SRES A2 run #4.

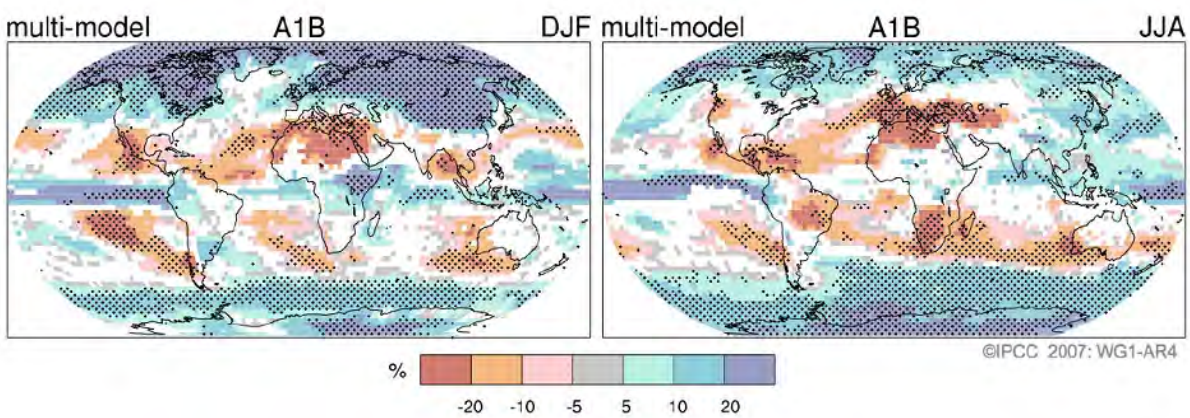

Fig. 3.2.6 Projected patterns of percentage changes in precipitation for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the A1B emission scenario. White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. DJF = winter, JJA = summer. (Figure 10.9 from WG 1 in IPCC AR4, 2007)

As baroclinic flows along the BC shelf are largely determined by salinity rather than temperature, freshwater discharges along the coast are important, not only for their direct role in generating coastal currents but also indirectly through the role they play in transporting larvae and nutrients and acting as possible barriers to cross-shelf transport, *e.g.*, from shelf-edge upwelling. Figure 3.2.6 shows that watersheds along the BC coast are projected to become wetter in winter (DJF) and drier in summer (JJA). As a significant amount of the winter precipitation away from the coast is stored as snow-pack and released later in the year, drier summers do not necessarily mean less discharge.

The main problem in estimating both historical and future freshwater discharge along the BC coast is that approximately 40% is ungauged. Morrison *et al*. (2011) have developed a technique for estimating ungauged runoff based on the precipitation, temperature, terrain characteristics, and storage capacity within 22 watersheds whose freshwater discharges affect coastal BC waters. The technique has been verified with historical observations and used to reconstruct historical time series. In order to employ the same technique to estimate future discharges, only future precipitations and temperatures need be specified and these have been downscaled from the same CRCM model output that was used to provide the atmospheric forcing. An earlier study that was restricted to only the Fraser River watershed (Morrison *et al*., 2002) and projections from the CCCma IPCC AR3 global model predicted only a modest (5%) increase in the average total annual discharge over 2070–2099, but increased flow over the winter and an earlier (by 24 days) spring melt and 18% smaller peak discharge.

At the time of writing this report, only preliminary future simulations with the BC regional climate model had been carried out. Average annual sea surface temperature anomalies for a 15-year future simulation with respect the 1995–2009 Masson and Fine (2011) hindcast are shown in Figure 3.2.7b as an example of these results. Warmer values are seen everywhere along the thalweg (Fig. 3.2.7a) traversing Juan de Fuca Strait, Haro Strait, and the Strait of Georgia, but due to a combination of tidal mixing and Fraser River discharge (which enters the Strait of Georgia at approximately 250 km along the thalweg), they are certainly not spatially uniform. More simulations and analyses are underway and their results will be summarized in a manuscript that will be submitted to a peer-reviewed journal.

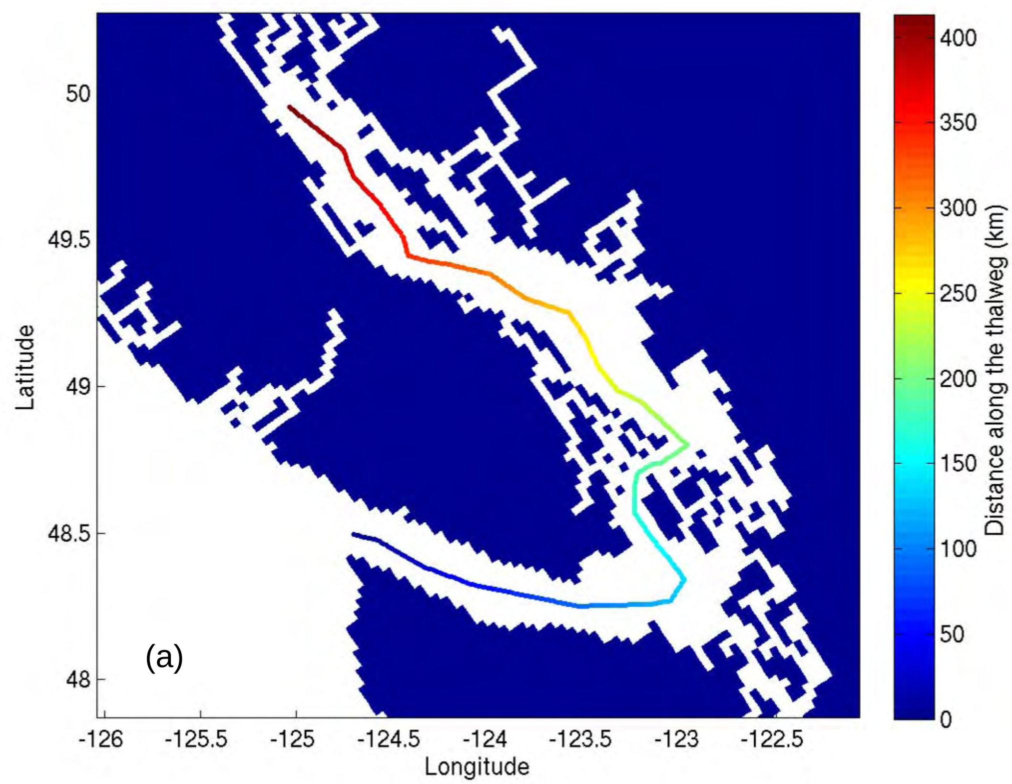

Fig. 3.2.7 (a) Model grid and thalweg along Juan de Fuca Strait, Haro Strait and Strait of Georgia.

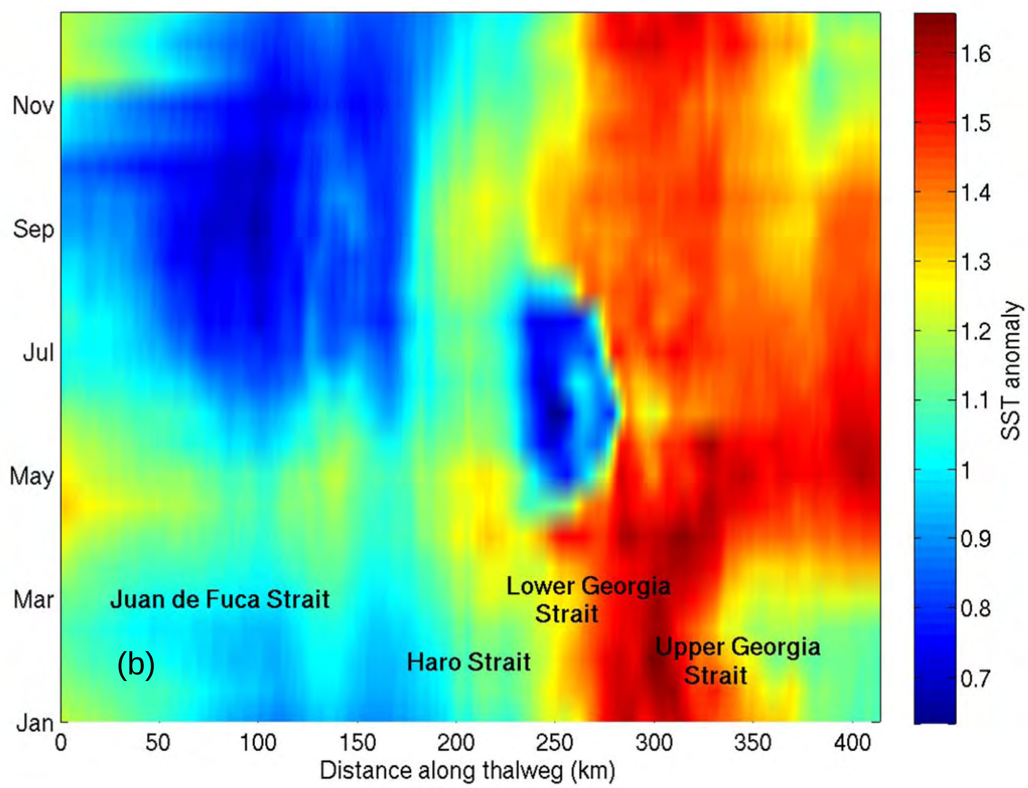

Fig. 3.2.7 (b) Annual average sea surface temperature anomalies (°C) along the thalweg.

III Trends in Upwelling and Downwelling Winds along the BC Shelf

As this section summarizes Foreman *et al.* (2011; henceforth FPM11), the interested reader is referred to that paper for more details.

Using the Bakun (1973) upwelling index to approximate the amount of water drawn upward from the base of the Ekman layer at 6 equally spaced sites between 33°N and 48°N, Bograd *et al.* (2009; henceforth B09) estimated trends and variability in coastal upwelling along the California Current System (CCS) over the period of 1967–2007. Cumulative upwelling indices (CUI, Schwing *et al.*, 2006) computed for each year and at each site were used to quantify the timing of the spring transition, the length of the upwelling season, and cumulative upwelling and downwelling strength. Among various statistically significant trends, they found that in the northern CCS the spring transition was becoming later and the upwelling season was becoming shorter at the respective rates of 1.0 day year^{-1} and 1.1 days year^{-1}.

FPM11 extended the B09 analysis northward to the waters off BC where the North Pacific Current bifurcates into the California and Alaska Currents (Dodimead *et al.*, 1963). Though upwelling is generally considered to be a characteristic of only the CCS and roughly extends from Vancouver Island to Baja California (Thomson, 1981), the latitude of the bifurcation (Freeland, 2006) and positions of the Aleutian Low and North Pacific High pressure systems all exhibit interannual variability so that northern BC waters can have a short upwelling season (Hsieh *et al.*, 1995). It is therefore useful not only to determine if the trends found by B09 extend to southern BC, but also how far that upwelling extends to the north and whether or not its timing and magnitudes have changed.

As described earlier, Faucher *et al.* (1999; henceforth F99) extended the Environment Canada network of weather buoys off the BC coast (Fig. 3.2.1) back to 1958, and the winds from the 6 stations closest to the shelf break (206, 132, 207, 147, 208, 205), rather than those derived from atmospheric pressure fields

(Bakun, 1973), were used to compute our BC CUIs. Specifically, the Faucher *et al.* (1999) version of these winds were used up to 1997 while for 1998–2007, gaps in the buoy observations were filled using the NASA archive of cross-calibrated, multi-platform (CCMP) ocean surface winds (Ardizzone *et al.*, 2009; (http://podaac.jpl.nasa.gov/DATA_CATALOG/ccmp info.html). See FPM11 for analyses of the differences between these data sets and the expected impact of combining them on the subsequent trend analyses.

Once all gaps were filled in the wind time series, the associated wind stresses, $\boldsymbol{\tau}$, were calculated using the bulk formula (Gill, 1982)

$$\boldsymbol{\tau} = \rho_a * C_\mathrm{d} * |\boldsymbol{v}|\boldsymbol{v}$$

where ρ_a is the air density (1.2 kg m^{-3}), C_d is a constant drag coefficient (0.0013) and $\boldsymbol{v}$ is the wind vector with magnitude $|\boldsymbol{v}|$. These stresses were then resolved into their alongshore and cross-shore components where, consistent with alongshore bathymetry and coastline orientations (Fig. 3.2.1), 30° counterclockwise from north was chosen as the alongshore direction for the 3 northern buoys while 45° clockwise from north was chosen for the southern ones. Offshore/onshore Ekman transports per 100 m of coastline were then estimated by dividing these alongshore stresses by the Coriolis parameter and density of seawater (Pickett and Schwing, 2006). At each buoy location, the CUI was calculated (Schwing *et al.*, 2006) by integrating the daily upwelling indices over the duration of the upwelling season and for each year, the spring and fall transitions were determined as the dates when the gradient of the CUI changed sign from negative to positive (spring) and *vice vers*a (fall). For each buoy location, decadal (or climatological) means were then computed by simply averaging the CUIs over 10 consecutive years and filtering with a 15-day running average to remove any remaining high frequency variability. Consistent with B09, the total upwelling magnitude index (TUMI) was computed as the difference between CUI values at the end and start of the upwelling period, and somewhat differently from B09, the total downwelling magnitude index (TDMI) was defined as the CUI value on December 31 minus the TUMI.

Decadally-averaged CUIs were computed for the F99, and observed + CCMP data sets are shown in Figure 3.2.8. The associated upwelling start and end dates are given in Table 3.2.3 and also shown in Figure 3.2.8. The estimation of confidence limits associated with these dates is complicated by numerous wiggles in the yearly CUIs, even after the application of a 15-day moving average filter. Though careful analysis of local *versus* global minima/maxima might permit the definition of start/end dates for each year, FPM11 used a bootstrap approach to estimate 90% confidence intervals for the values listed in Table 3.2.3. These limits are usually less than about 20 days and comparable to those listed in Table 1 of B09, but in some instances they can be much larger. The interested reader is referred to FPM11 for further details.

Table 3.2.3 Decadal average start (first number, Julian day number) and end (second number) dates of the upwelling season at the 6 weather buoys located close to the shelf break along the BC coast.

Buoy/decade	1959–1968 (F99)		1969–1978 (F99)		1979–1988 (F99)		1989–1998 (F99)		1999–2008 (obs + CCMP)	
206	89	275	78	283	105	272	118	277	113	271
132	94	275	118	274	127	272	119	279	113	280
207	97	251	153	264	144	270	122	276	151	276
147	169	249	158	231	149	266	125	271	151	263
208	100	251	154	262	144	267	122	264	151	270
205	174	245	159	232	190	236	128	244	209	225

F99 – Faucher *et al.* (1999)
CCMP – cross-calibrated, multi-platform data set

Visual inspection of the upwelling start dates shown in Figure 3.2.8 suggests that despite some interdecadal variability, there may be trends towards later onsets at all buoys except 147. In fact, there are and FPM11 compute them to be 0.88, 0.39, 0.77, –0.69, 0.70, and 0.23 days per year for buoys 206, 132, 207, 147, 208, and 205, respectively. All are significantly different from zero at the 95% level and at all buoys except 147 upwelling is becoming later, a trend consistent with, though smaller than the 1.0 days year^{-1} value that B09 found at their 48°N site. A similar analysis was carried out for the upwelling season durations and again, at all buoys except 147, the trend was becoming shorter. In this case, all trends except that for buoy 207 were significantly different from zero at the 95% level and the value for buoy 206 was –1.02 days year^{-1}, very close to the –1.1 days year^{-1} that B09 found at their 48°N site. The contrary trends toward an earlier spring transition and longer upwelling season at buoy 147 are interesting and may arise from changes in the seasonal winds in Hecate Strait and Queen Charlotte Sound, even though opposite trends were found at buoy 207, which should also be affected by similar changes. As seen in Figure 3.2.1, Environment Canada has three buoys in this region (204, 185, 183) and F99 also extended their time series back to 1958. So it would be feasible to employ an analysis similar to what has been done here to see what trends emerge. This has not been done yet but is planned for the future.

Table 3.2.4 lists 5 decades of TUMI and TDMI values associated with the Figure 3.2.8 CUIs while Figure 3.2.9 displays these data in graphical form, along with linear trends that have been fit via least squares. Note that the TUMIs do not decrease monotonically from south to north. The largest TUMIs are at the second most southerly buoy (132) while the fifth buoy (208) displays more upwelling than the fourth (147). Although there is considerable inter-decadal variability and a notable decline in upwelling over the last decade at all but buoy 206, all TUMIs except 205 show an overall increase over the past 5 decades, with the largest trends (Table 3.2.4) being at buoys 132 and 207. The trends at buoys 206, 132, 207, and 147 are significantly different than zero at the 95% confidence level while that for buoy 208 is significant at the 90% level. Transforming these trends into 40-year changes in the associated upwelling-favourable winds, the last column in Table 3.2.4 shows increases ranging between 0.9% (205) and 25.7% (147).

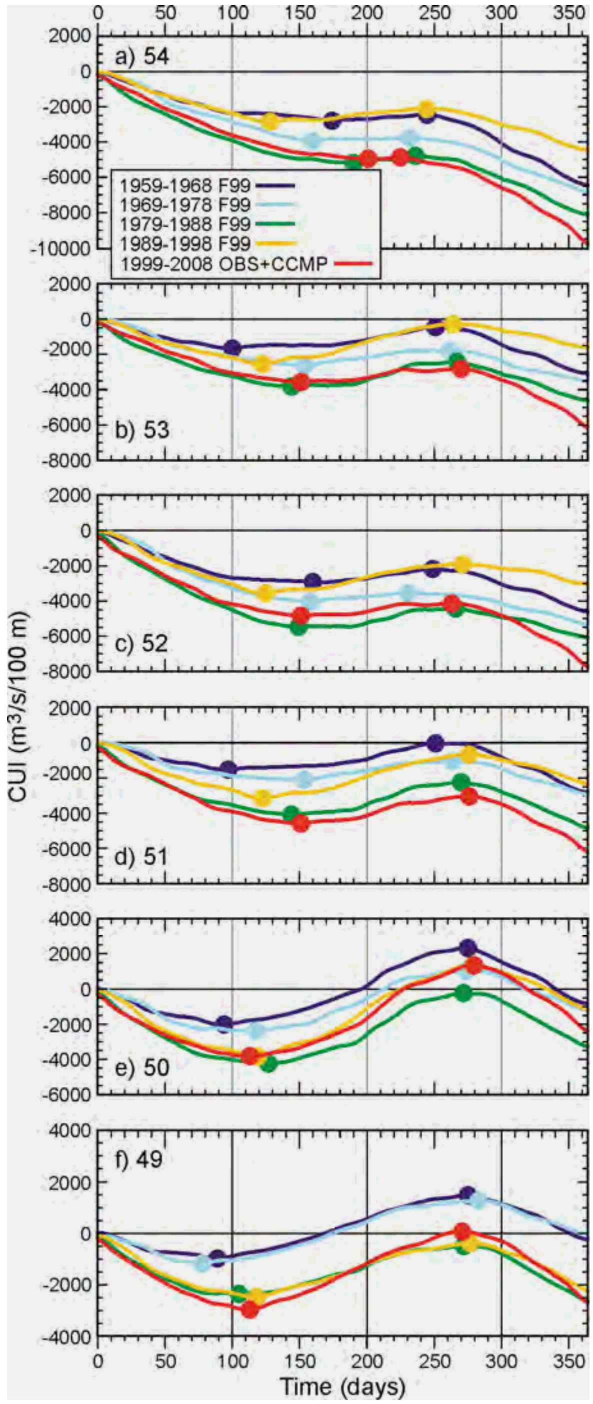

Fig. 3.2.8 Decadal-average CUIs (cumulative upwelling indices) for 1959–2008 at weather buoys (a) 205, (b) 208, (c) 147, (d) 207, (e) 132, and (f) 206. CUIs for the first 4 decades were computed from the F99 time series while those for the last decade used observed buoy winds with gaps filled from the CCMP data set. Solid circles denote the start and end of the upwelling season. Labels 49–54 denote buoy latitudes rounded to the nearest degree.

Table 3.2.4 TUMI (total upwelling magnitude index; top number) and TDMI (total downwelling magnitude index, bottom number) decadal averages ($m^3 s^{-1}$ per 100 m of coastline), linear trends ($m^3 s^{-1}$ per 100 m $year^{-1}$), and associated percentage wind increase over 40 years at the 6 weather buoys close to the shelf break along the BC coast. * and # denote trends that are significantly different from zero at the 90 and 95% levels, respectively.

Buoy/ decade	1959–1968 (F99)	1969–1978 (F99)	1979–1988 (F99)	1989–1998 (F99)	1999–2008 (obs+CCMP)	Mean (F99+ obs/CCMP)	Linear trend	% wind speed increase
206	2457	2453	1859	2093	3041	2381	8.1#	7.0
	–2647	–2478	–4563	–4445	–5826	–3992	–83.3#	55.9
132	4344	3420	4000	5189	5168	4424	34.2#	16.9
	–5095	–4627	–7367	–6531	–7661	–6256	–70.4#	25.7
207	1489	1050	1845	2470	1542	1679	15.3#	20.2
	–4228	–4008	–6808	–4946	–7817	–5561	–81.2#	35.1
147	754	482	1030	1655	686	921	10.4#	25.7
	–5362	–5870	–7177	–4718	–8582	–6341	–52.9#	18.3
208	1204	849	1411	2259	737	1292	4.8#	7.7
	–4232	–4412	–6096	–3947	–7085	–5154	–52.4#	20.9
205	342	167	406	730	91	343	0.2*	0.9
	–6782	–7073	–8646	–5246	–10054	–7556	–46.7#	13.2

F99 – Faucher *et al.* (1999)
CCMP – cross-calibrated, multi-platform data set

Although the largest and smallest (negative) TDMI values (Fig. 3.2.9b) arise at the most northerly and southerly buoys, namely 205 and 206, TDMIs at the buoys in between do not display a monotonic progression from north to south. The second smallest TDMI is at the second most northerly buoy (208) and the third largest is at second most southerly buoy (132). Though all TDMIs show a 1989–1998 decrease in downwelling that becomes progressively stronger to the north, all linear trends show increased downwelling with particularly strong increases over 1999–2008. All trends are significantly different from zero at the 95% level, with the largest values being at buoys 206 and 207. The associated 40-year increases in downwelling-favourable winds range between 13.2% (205) and 55.9% (206).

An intensification of TUMI and TDMI along the BC shelf over the last 50 years begs the question of whether these trends might continue in the future. As described in section I, Merryfield *et al*. (2009) showed that ensemble mean summer winds along the BC shelf in the late 21st century were forecast to increase in speed by 5 to 10% and rotate clockwise by ≈5°, both statistically significant changes, while the associated ensemble winter winds showed no statistically significant changes. Though these changes are considerably less than the historical upwelling- and downwelling-favourable wind changes found here, in their GCM analyses both Yin (2005) and Salathé (2006) found a deepening and northward shift of the Aleutian Low accompanied by a northward shift in North Pacific storm tracks that would be a consistent continuation of our TDMI trends. Perhaps more importantly, Gillett *et al*. (2003) not only found trends in December–February Northeast Pacific sea level pressures over 1948–1998 that are consistent with stronger downwelling-favorable winds in the California Current region, but they also demonstrated that anthropogenic greenhouse gases and sulphate aerosols have had a detectable influence on sea level pressures over the second half of the 20th century. This suggests that these pressure trends (and hence the associated intensifying winds) should persist with continuing emissions.

Though Global Climate Models (GCMs) have been to used to forecast future changes in the seasonality and magnitude of winds and river discharges (Morrison *et al*., 2002), further study with coupled ocean–atmosphere regional climate models that have much finer horizontal resolution than the >1° that is common to most GCMs will be necessary to provide more credibility and spatial detail. As described in section II, such a regional climate model is presently under development for the British Columbia continental shelf and results from its simulations should be available soon.

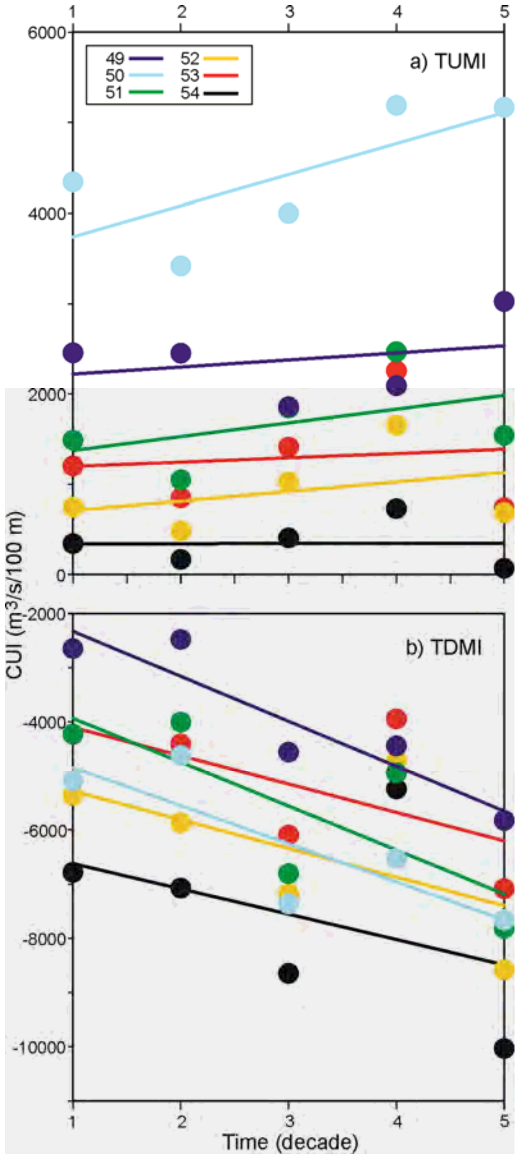

Fig. 3.2.9 (a) TUMI (total upwelling magnitude index) and (b) TDMI (total downwelling magnitude index) values (solid circles) and linear trends over the past 5 decades at the 6 weather buoys located close to the shelf break along the BC coast. Labels 49, 50, 51, 52, 53, and 54 denote buoy latitudes rounded to the nearest degree and correspond to buoys 206, 132, 207, 147, 208, and 205, respectively.

Acknowledgments We thank the Centre for Ocean Model Development for Application (COMDA) within Fisheries and Oceans Canada (FOC) for the funding to support the development of the BC shelf model and to purchase the 256 processor computer on which that model runs. We also acknowledge the Climate Change Science Initiative (CCSI) and Ecosystem Research Initiative (ERI) within FOC for their financial support of this climate research.

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3.3 Ecosystem projections for the Kuroshio-Oyashio system

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Kuroshio-Oyashio System

The Kuroshio and Oyashio systems are western boundary currents within the subtropical and subarctic circulation gyres of the North Pacific, respectively (Stommel and Yoshida, 1972). The Kuroshio Current separates from the Japan coast at Boso Peninsula, and turns to the east as the Kuroshio Extension, which shows typical meanders and generates mesoscale eddies by instabilities. The Kuroshio is characterized by warm, highly saline oligotrophic waters of the subtropical gyre. Wintertime mixing also provides nutrients to the sea surface. However, the water column is weakly stratified even during winter and the extent of the spring bloom is much smaller than that in the Oyashio. Spring bloom in the Kuroshio is usually observed in February to March (Nagata, 1998). Primary production in the Kuroshio is considered to be limited basically by nutrient availability, as in the other subtropical regions (Polovina *et al.*, 1995).

The Oyashio flows southward along Hokkaido Island and Honshu Island, and turns to the east with meanders. The eastward flowing Oyashio makes the Subarctic Front (Oyashio Front) which is a distinctive temperature front. In the region between the Subarctic Front and the Kuroshio Extension (called as the Kuroshio-Oyashio Transition Zone), cold and warm waters mix with each other in a complex manner, forming many mesoscale features. The Oyashio is characterized by low temperature, low salinity, and high nutrients. Nutrient supply by wintertime mixing triggers an extensive spring bloom during late April to May at the time when the mixed layer depth becomes shallower than the critical depth.

One of the distinctive features of the Kuroshio-Oyashio system is the large contrast of environments to latitudinal direction. Small pelagic fish in this area spawn in the subtropical region and migrate to feed in the highly productive subarctic region. The size of dominant zooplankton increases with latitude, and the start of active plankton production is early in the south and later in the north. Therefore, the ontogenetic migration in the Kuroshio-Oyashio system is favorable for these small pelagic fish (Ito *et al.*, 2004). More detailed descriptions of Kuroshio-Oyashio system are described in Yatsu *et al.* (2011).

Approaches to End-to-End Ecosystem Modeling

Marine ecosystem and fish resources are affected by various factors, including climate change and human impacts. We consider the marine system in terms of the following three components (Fig. 3.3.1): (1) the various environmental factors surrounding the marine ecosystem (*e.g.*, oceanic physical environment, atmospheric CO_2 concentration, river discharge of nutrients, aerial dust deposition), (2) the lower-trophic level marine ecosystem (LTLE), including biogeo-chemical cycles, and (3) fish resources as the higher-trophic level ecosystem (HTLE). Each component involves strong interactions of essential physical, chemical or biological processes. In the case of the climate system, the air–sea interactions associated with climate change, *e.g.*, global warming, decadal and interannual variations like PDO (Pacific Decadal Oscillation) or ENSO (El Niño Southern Oscillation), cause significant changes in the physical environment, *i.e.*, temperature, strength of stratification, light intensity reaching to the sea surface, and ocean circulation. In the LTLE, a linkage between the nutrients cycle and biological production, which also relates to ecosystem structure, is one of the most important relationships. For the HTLE, intra-specific or inter-specific competitions between fish could play significant roles for a variety of fish resources.

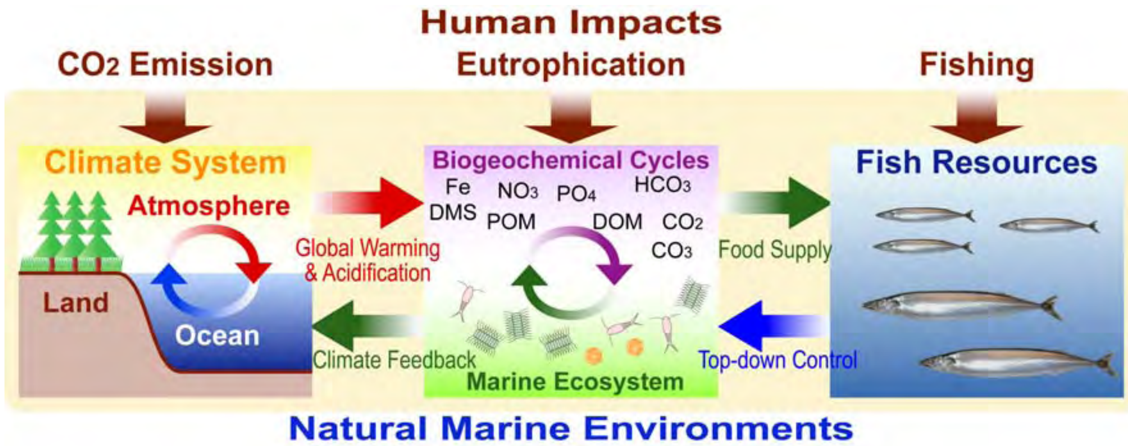

Fig. 3.3.1 Components of natural marine environments. The climate system is modified by global warming which results from anthropogenic CO_2 emission. Climate change, especially global warming and ocean acidification, as well as man-made eutrophication, affect marine biogeochemical cycling and ecosystems. They also give rise to a feedback in the climate system by modifying the ability of phytoplankton to absorb anthropogenic CO_2. The changes in marine ecosystems and fishing pressure control the amount of aquatic resources which, in turn, strongly affects the lower-tropic level ecosystem, including zooplankton and phytoplankton.

For comprehensive understanding, we must also consider the interactions between the three components. For example, the temperature increase associated with global warming strengthens stratification, which decreases nutrient supply to the surface water. On the other hand, a rise in temperature generally tends to enhance growth rates of the LTLE, and the strengthened stratification could enhance the light environment for photosynthesis. These changes in the LTLE (*e.g.*, biomass, production, or species) and physical environment also affect the HTLE. The changes in physical environments (*e.g.*, temperature and ocean circulation) can also directly affect the growth and distribution of fish resources. In addition to these bottom-up effects from climate to the HTLE, top-down effects from the HTLE to the LTLE, resulting from differential feeding of predators on phytoplankton and zooplankton, could exert important controls on species dominance (Suda *et al.*, 2005; Yatsu *et al.*, 2005). Feedback processes from the changes in the LTLE to climate have also been suggested, *e.g.*, changes in production of dimethylsulphide (DMS; an important climate reactive gas) produced by phytoplankton could cause a negative feedback to counter warming due to climate change (Charlson *et al.*, 1987). Moreover, human impacts like emissions of anthropogenic CO_2, eutrophication and overfishing affect each system. Therefore, efforts to clarify both the bottom-up and top-down effects are important for a comprehensive understanding of interactions and for quantitatively evaluating each process.

Two essential requirements must be considered for comprehensive modeling to evaluate the impacts of climate change on marine ecosystems. One is the adequate representation of changes in physical environments (*e.g.*, temperature, currents, depth of the mixed layer and intensity of solar radiation) which are important for ecosystem changes. It is also desired to reproduce spatio-temporally heterogeneous environments from coastal to basin scales, and from seasonal to interannual or decadal scales. The other requirement is explicit representations of the ecosystem structure and biogeochemical processes at each trophic level. An ideal simulation for future projection or hindcast of ecosystem changes should employ a fully integrated climate model including fish and ecosystem components with two-way interactions. However, such an approach is difficult due to practical restrictions of computational resources and uncertainties of ecosystem dynamics, and we need to reduce the physical (*i.e.*, horizontal or vertical resolutions) or biogeochemical (*i.e.*, species or processes) resolutions.

To evaluate spatio-temporally heterogeneous changes in the LTLE, many 3-D biogeochemical models have been developed as one-way coupling of the hydrodynamic and LTLE models (*i.e.*, the ocean currents and other physical properties of the system drive the biological dynamics but there is no feedback from the biological dynamics to the physics), as reviewed in Hood *et al.* (2006). Many approaches have also been taken to represent the fish-centered

HTLE and relationship with the LTLE, as reviewed in Travers *et al.* (2007). However, in many cases focusing on the higher-trophic level food web, only limited hydrodynamics information has been used in the HTLE models (*e.g.*, the physical component of the HTLE model is represented as a zero-dimensional model or a few box models). Even if focusing on changes in the hydrodynamic environment with the HTLE, the information for the LTLE is more limited, *e.g.*, to primary production without considering plankton composition. In order to link models from climate to fish, end-to-end, a one-way information transfer analogous to the relay with a baton, is useful as a first step, especially for planktonic community dynamics which are largely governed "bottom-up" by physical forcing (*e.g.*, Margalef, 1978). In other words, biogeochemical and ecosystem models project the impacts of climate change onto the LTLE based on the physical environments reproduced or projected by a climate model. In the LTLE models, the top-down effects from higher predators usually represent as a quadratic mortality term for the highest trophic level, which is essentially representing the biomass of unresolved fish and other predators scale in proportion to the biomass of their prey. Using the results of the LTLE, a fish resources model projects the impacts onto the HTLE, including the changes in various plankton components in response to changes in the physical environment. In fact, these bottom-up relationships to fish resources are shown in some studies. Using trophic dynamic models applied to ocean data, Iverson (1990) showed that carnivorous fish production is controlled by the availability of inorganic nutrients incorporated into the phytoplankton biomass and transferred through food webs in North American coastal waters. Ware and Thompson (2005) also showed a highly correlated relationship between primary production and the resident fish yield in the continental margin of western North America, using annual fish catch data and satellite-derived chlorophyll-***a*** measurements.

Previous Studies Approaching End-to-End Ecosystem Modeling

As an example of the baton relay from climate change to fish via the LTLE, there is a comprehensive framework applied to a case of inter-decadal climate variability in the North Pacific. Aita *et al.* (2007) developed a global 3-D LTLE model, COCO-NEMURO, which is the North Pacific Ecosystem Model Used for Regional Oceanography (NEMURO, Yamanaka *et al.*, 2004; Kishi *et al.*, 2007; Fig. 3.3.2) coupled with the CCSR Ocean Component Model (COCO, Hasumi, 2000). Using National Centers for Environmental Prediction, NOAA National Weather Service/National Center for Atmospheric Research (NCEP/NCAR) 6-hourly re-analysis dataset of sea surface temperature, freshwater flux, surface wind stress and solar radiation for the period 1948–2002, they simulated inter-annual variation of the LTLE associated with the Pacific Decadal Oscillation (PDO), focusing particularly on the 1976/1977 climate regime shift. The model successfully reproduced the observed decrease in primary production and diatom-grazing mesozooplankton biomass (Tadokoro *et al.*, 2004). As a direct receiver of information of changes in the LTLE, a fish bioenergetics-based population dynamics model coupled with NEMURO (NEMURO For Including Saury and Herring: NEMURO.FISH) was also developed (Megrey *et al.*, 2007). Using NEMURO.FISH with the results of Aita *et al*. (2007), wet weight of individual saury in the western North Pacific was simulated to have decreased after the 1976/1977 climate regime shift, due primarily to cooling (Ito *et al.*, 2007). Rose *et al.* (2007) also showed regionally different responses of herring growth in the mid and late 1970s in the northeastern Pacific, *i.e.*, herring growth rate decreased off the West Coast of Vancouver Island and in Prince William Sound, but increased in the Bering Sea. This is because the herring growth rate is positively correlated with two factors, water temperature and abundance of zooplankton as a prey, and only one of these two factors determines the herring growth rate in each oceanic region, respectively. This baton relaying framework worked effectively for evaluating impacts of climate change, end-to-end. These evaluations of inter-decadal variability in the past serve as a validation of the models to be used to project impacts of future climate change.

Future responses of the LTLE to global warming have been discussed in several previous studies using 3-D LTLE models with simulated physical fields from climate models. As a pioneering study, Boyd and Doney (2001) conducted a global warming simulation with projected physical fields from the NCAR Community Climate System Model (Boville and Gent, 1998) following the IPCC (Intergovernmental Panel on Climate Change) SRES (Special Report on Emissions Scenarios) A1 scenario, which expects very rapid economic growth with increasing globalization. They suggested significant changes by

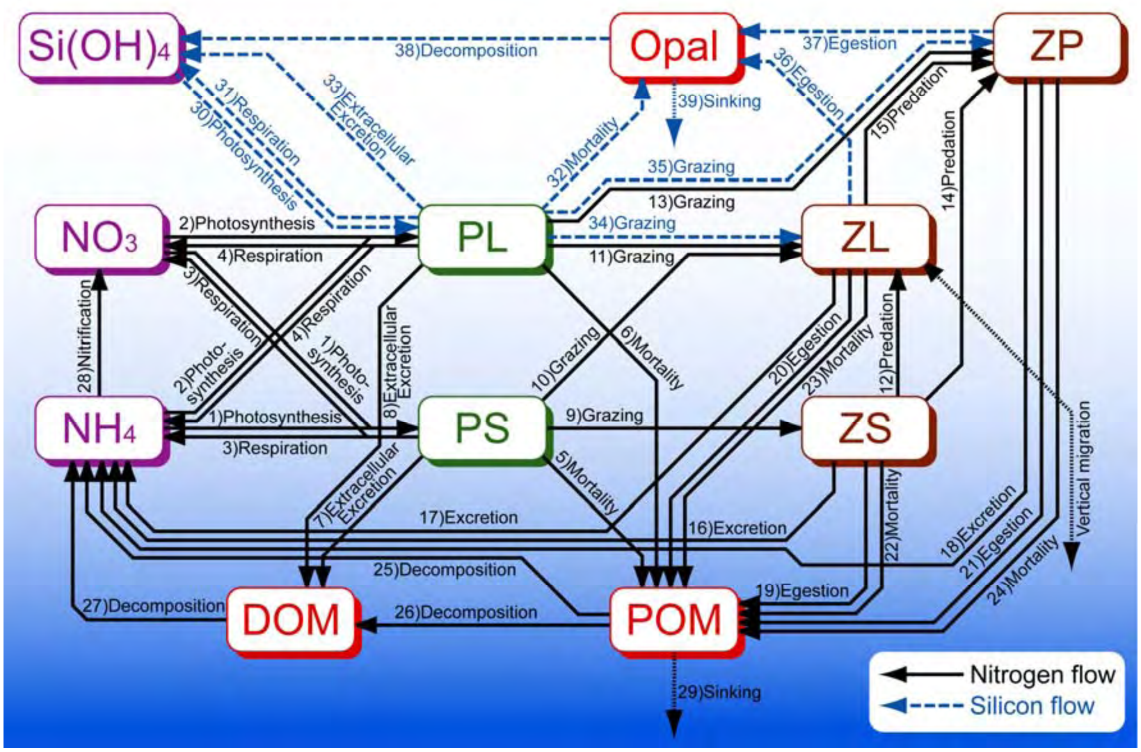

Fig. 3.3.2 Schematic view of the NEMURO lower-trophic level ecosystem model (from Kishi *et al.*, 2007). Solid black arrows indicate nitrogen flows and dashed blue arrows indicate silicon.

the end of this century in ecosystem structure, with some of the largest regional impacts, especially increases in nitrogen fixers in the subtropical regions due to strengthened stratification. Using the same kind of approach, it is also generally suggested that rising temperatures in high latitudes lead to strengthened stratification and decreased nutrient supply to surface waters. As a result, it has been suggested that the annually averaged response to global warming will include decreases in chlorophyll in the high latitude ocean of high productivity (*e.g.*, Sarmiento *et al.*, 2004; Schmittner *et al.*, 2008) and changes in phytoplankton composition, *i.e.*, shifts from diatoms to small phytoplankton groups associated with depleted nutrient conditions (Bopp *et al.*, 2005; Hashioka and Yamanaka, 2007a, hereafter HY07a). As an impact on the seasonal cycle, HY07a also suggested earlier onset of the spring bloom in the western North Pacific, with a decrease in maximum biomass associated with strengthened stratification. They concluded that global warming will not impact uniformly on marine ecosystems in all seasons, but that effects will be significantly greater at the end of the spring bloom. Therefore, in order to project impacts on the HTLE based on the changes in the LTLE, it is essential to reproduce the effects of warming on seasonal dynamics that can vary over regional scales (*i.e.*, 100s of kms).

A few studies have been made in future projections of the HTLE using the baton relay approach using the LTLE results, including information of plankton compositions with a horizontally heterogeneous physical environment. As one example, recently Kishi *et al.* (2009) applied a bioenergetics model, NEMURO.FISH, to Japanese common squid, *Todarodes pacificus*, and conducted a global warming simulation. The time-dependent horizontal distribution of zooplankton as prey of common squid under the global warming condition was calculated by a 3-D LTLE model, COCO-NEMURO in HY07a following the IPCC IS92a scenario (*i.e.*, atmospheric CO_2 concentration reaching 788 ppm in the year 2100). Based on these projected results of the LTLE, they showed a possibility that wet weight of common squid decreases due to rising temperatures exceeding the optimum range for growth of common squid. This result suggests that the migration route and spawning area of common squid might change with global warming. As another example, Lehodey *et al.* (2009)

projected the potential impacts of global warming on the population of bigeye tuna, *Thunnus obesus*, a top predator of the pelagic ecosystem, in the Pacific Ocean under the IPCC SRES A2 scenario for the 21st century (*i.e.*, atmospheric CO_2 concentration reaching 850 ppm in the year 2100) using the Spatial Ecosystem and Population Dynamics model (SEAPODYM; Lehodey *et al.*, 2003). This model includes an enhanced definition of habitat indices, movements, and accessibility of tuna predators to different vertically migrant and non-migrant micronekton functional groups. The simulations are driven by the predicted bio-physical environment from the Institut Pierre Simon LaPlace (IPSL) climate model version 4 (IPSL-CM4) coupled to the oceanic biogeochemical model Pelagic Interaction Scheme for Carbon and Ecosystem Studies (PISCES; Aumont *et al.*, 2003). In this experiment, they demonstrated the potential future changes in distribution and abundance of bigeye tuna, *i.e.*, an expansion of the spawning habitat and density of larvae, especially in the eastern tropical Pacific as a result of the temperature increase and changes in productivity and ocean circulation.

Future Projections of Ecosystem Change in the Kuroshio-Oyashio System

Although the studies cited above applied challenging approaches for future projections on global or basin scales, there are still some important points which should be addressed on the regional scale or seasonally specific events. Most future projections of ecosystem change, not only the LTLE but also the HTLE, had been conducted using results of coarse-resolution climate models (*i.e.*, 1 to 3° in the oceanic component; IPCC, 2007) due to limited computational resources. However, coarse-resolution models cannot reproduce certain physical features which play significant roles in ecosystems, especially in the Kuroshio-Oyashio system, that is, meso-scale features, current speed, and separation latitude of the Kuroshio current. Therefore, the projected ecosystem responses from coarse-resolution models are much different from those obtained from higher-resolution models. As an example, using a high-resolution climate model which can represent the key features of the Kuroshio, Sakamoto *et al.* (2005) suggested that the current speed is accelerated by as much as 30% under global warming at the end of the 21st century, while the separation latitude of the Kuroshio does not change. These reproductions of heterogeneous physical environments are required for the evaluation of impacts of climate change on migration routes or distributions of pelagic fishes. We report our approach for end-to-end modeling for future projection of impacts on the marine ecosystem with examples for the LTLE (Hashioka *et al.*, 2009) and for the HTLE (Okunishi *et al.*, submitted) in the Kuroshio-Oyashio system. Although simulations by high-resolution ecosystem models in many cases must use downscaled results of coarse-resolution climate models, in our case the projected physical environment from the only high-resolution climate model, the Model for Interdisciplinary Research on Climate (MIROC) version 3.2 (K-1 Model Developers, 2004), in the IPCC 4th Assessment Report (IPCC, 2007) permitted a direct evaluation of impacts on the marine ecosystem without the necessity of downscaling.

Future projections for the LTLE

We developed a regional version of our 3-D high-resolution ecosystem model, COCO-NEMURO, applying it to the upper 1500 m in the western North Pacific (about 110°E–180°, 10°–60°N) with an offline calculation method. NEMURO incorporates both multi-nutrient limitation (NO_3, NH_4 and $Si(OH)_4$) and a description of the plankton community structure with five Plankton Functional Types (PFTs; diatoms, non-diatom small phytoplankton, and three zooplankton groups), as described in Kishi *et al.* (2007). Climate-induced changes in ocean physics are estimated from a high-resolution set-up (*i.e.*, horizontal grid-spacing of 0.28° (zonally) × 0.19° (meridionally) in the ocean component) of the MIROC version 3.2 (K-1 Model Developers, 2004). As the physical component of our ecosystem model, COCO, is the same as the ocean part of MIROC, the projected physical field from MIROC can be used directly for offline calculation of our ecosystem model. In this study, in order to focus on the impacts on the seasonal cycle, we used the daily averaged high-frequent physical field from MIROC integrated in two configurations (Sakamoto *et al.*, 2005; Sakamoto and Hasumi, 2008). One is a pre-industrial simulation with fixed external forcing at levels of the year 1900. The other is a global warming simulation, where the atmospheric CO_2 concentration is increased at the rate of 1% year^{-1} from the pre-industrial condition, which doubles CO_2 concentrations after about 70 years. To drive the offline ecosystem model, we used 10-year datasets of pre-industrial (46th–55th simulated years of 295.9 ppm) and global warming (76th–85th around 656 ppm) simulations, and compared both results for the analysis.

For the 2xCO2 condition, annually averaged projected responses of the LTLE to global warming from our model supports the general conclusions of previous studies (*e.g.*, Boyd and Doney, 2001; Bopp *et al.*, 2005; HY07a), that is, an increase in temperature of 2 to 3° C in the western North Pacific leads to the strengthened stratification and decrease in nutrient supply to the surface water. As a result, phytoplankton and zooplankton concentrations are also decreased by 10 to 30%. We also investigated how the spring bloom responds seasonally and regionally to global warming under a more realistic environment in the high-resolution model. Our model reasonably reproduced the major features of the spring bloom: the bloom starts from the Kuroshio Extension region and moves northward, and in the subarctic region it occurs in coastal areas and moves to the open ocean (Fig. 3.3.3a–d). The projected changes in timing of the maximum concentration in the spring bloom becomes 10 to 20 days earlier than in the pre-industrial simulation in almost all regions in the western North Pacific (Fig.3.3.3e). This is mainly caused by the favorable temperature conditions at the beginning of the spring bloom and by the shortage of nutrients at the end of the bloom associated with decreased nutrient supply in winter. This projected response to global warming supports the results of the previous study, about a half month earlier (HY07a), and is statistically significant (< –95% in Fig. 3.3.3f) over wide areas compared with the natural variations.

On the other hand, projected changes in the maximum chlorophyll concentration of the spring bloom are not regionally unique (Fig. 3.3.3g). In the southern part of the Kuroshio Extension region (< 30°N), the maximum concentration decreases by 20 to 40% due to strengthened stratification. In the subarctic region, where top-down control has an important role in spring (Hashioka and Yamanaka, 2007b, hereafter HY07b), the maximum concentration decreases by 20 to 40% due to the increased grazing rate of zooplankton with rising temperature. However, in the northern part of the Kuroshio Extension region, where the physical environment is greatly improved in our eddy-permitting model, it is interesting that the maximum concentration during the spring bloom increases by 20 to 40%, associated with global warming, although the annually averaged phytoplankton concentration slightly decreases. These responses to global warming are statistically significant compared with the natural variations. The projected changes in the LTLE might affect the migration route or abundance of adult pelagic fishes. Our results suggest that even though the annually averaged properties change little, global warming could have large impacts on species and biogeochemical processes associated with seasonal events.

Future projections for the HTLE

In order to evaluate impacts of climate change on the pelagic fish ecosystem, Okunishi *et al.* (2009) developed an individual-based fish migration model and applied it to Japanese sardine, *Sardinops melanostictus*, which is one of the commercially important species in the western North Pacific. The individual-based model (IBM) is composed of a bioenergetics sub-model and a Lagrangian transport sub-model. Fish movement is controlled by feeding and spawning migrations with passive transport by simulated ocean currents. Feeding migration was assumed to be governed by the search for local optimal habitats, which is estimated by the spatial distribution of the net growth rate of a sardine bioenergetics model. The forage density is one of the most important factors which determine the geographical distributions of Japanese sardine during their feeding migrations. Spawning migration was modeled by an artificial neural network (ANN) with an input layer composed of five neurons that receive environmental information (surface temperature, temperature change experienced, current speed, day length and distance from land).

To investigate the impact of global warming on the pelagic fish ecosystem, we conducted both control and elevated CO_2 experiments using the fish migration model forced by the predicted physical environment (*i.e.*, sea surface current and sea surface temperature in the surface 30 m) from the high-resolution climate model, MIROC, and simulated surface prey density (vertically averaged small and large zooplankton and diatoms in the surface 30 m) by the LTLE model, COCO-NEMURO. They addressed the following key questions: (1) changes in the optimal spawning grounds and season associated with global warming and (2) changes in the geographical fish distributions at the adult stage during the harvest season in summer.

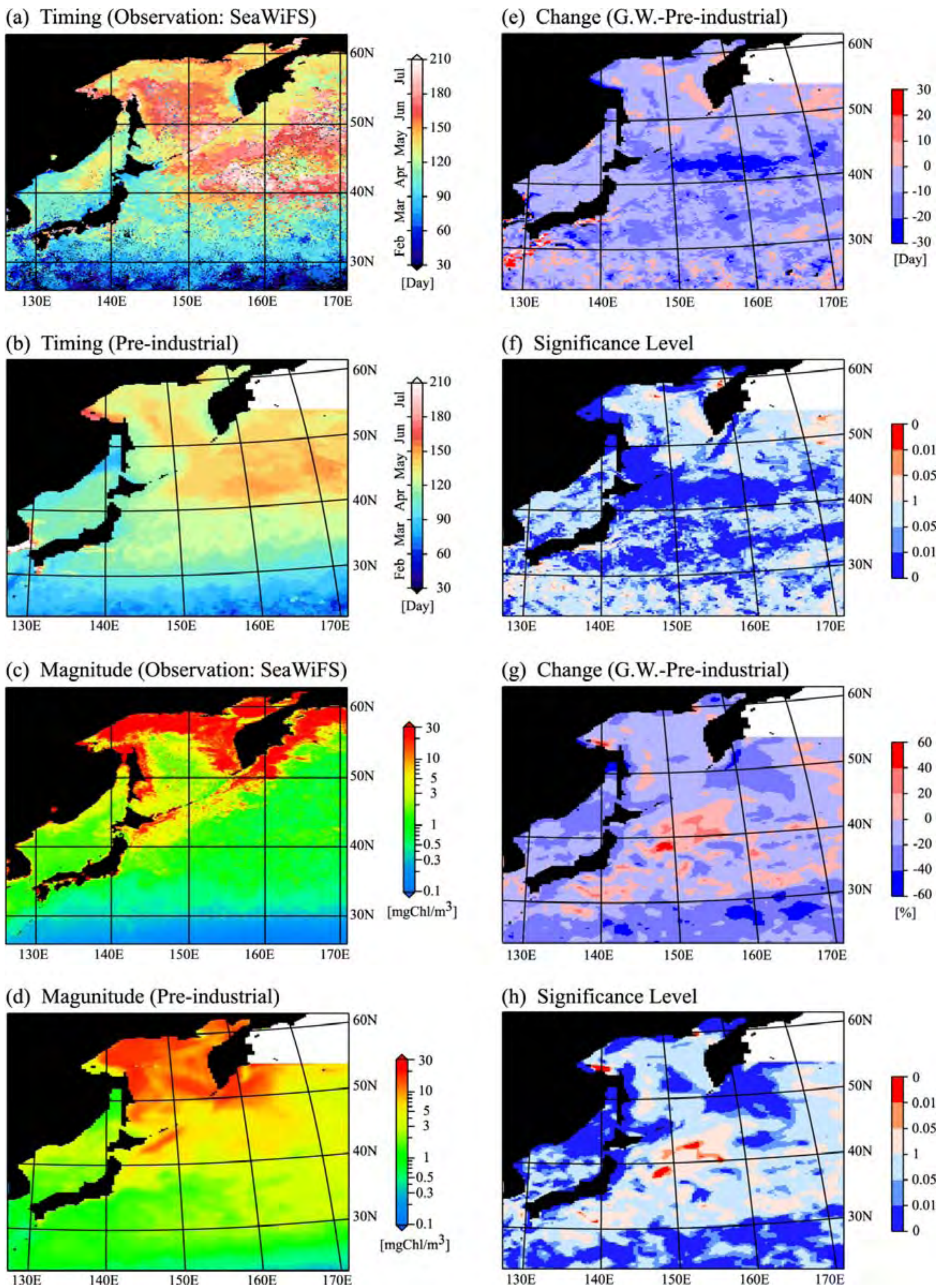

Fig. 3.3.3 Timing of the maximum chlorophyll concentration in the spring bloom in Julian days (from Hashioka *et al.*, 2009): (a) satellite-derived and (b) simulated. Magnitude of the spring bloom in mg Chl m^{-3}: (c) satellite-derived and (d) simulated. Projected changes (global warming minus pre-industrial) in (e) timing in days and (g) magnitude in percentage. Significance levels (*p*-values) from the Student's t-test for (e) timing and (h) magnitude, respectively, with areas of positive (negative) change shaded red (blue).

The model results demonstrated the possible impacts of global warming on the migration pattern and growth of Japanese sardine. The projected frequency of low-weight 4-month sardine (< 1 g) in the main spawning ground (*i.e.*, near Tosa Bay, south of Shikoku Island, Japan) is significantly higher in the global warming simulation (relative to the present-day case) because juvenile sardines were exposed to temperatures higher than optimal for feeding. Because smaller fish have higher mortality rates, this result suggests that the recruitment rate could decrease under global warming (Fig. 3.3.4). As a result, sardines were predicted to shift their spawning areas northward to avoid a collapse in their recruitment. During the northward migration period in summer, the geographical distribution of fish was projected to shift northward by 1 to 2° under global warming as the optimal temperature region for feeding expands northward due to rising temperature.

The Next Generation of End-to-End Models

The effects of feedbacks between the LTLE and climate should also be considered as two-way interactions. One of the most important feedbacks concerns changes in the strength of the biological pump associated with climate change. The Coupled Carbon Cycle Climate Model Inter-comparison Project (C4MIP; Friedlingstein, 2006) was designed to compare and analyze feedbacks between the carbon cycle and climate in the presence of external climate forcing. Recently many feedback processes related to changes in phytoplankton compositions (*e.g.*, changes in N_2 fixers, calcifiers, DMS producers and silicifiers) have been suggested, and modeling approaches have been tried to evaluate the effect of such feedback processes, as reviewed in Boyd and Doney (2003). To first order, the impacts of these feedbacks associated with changes in plankton compositions are

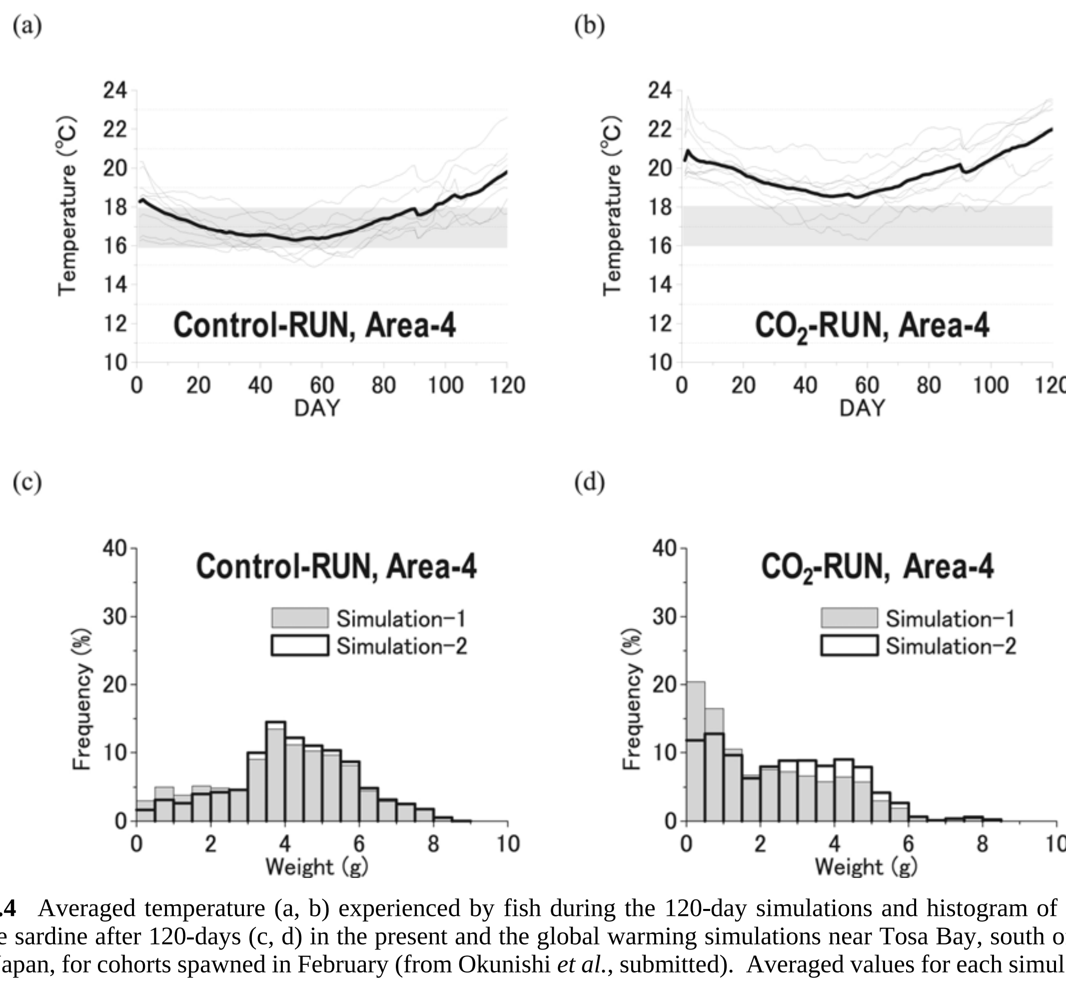

Fig. 3.3.4 Averaged temperature (a, b) experienced by fish during the 120-day simulations and histogram of weight of Japanese sardine after 120-days (c, d) in the present and the global warming simulations near Tosa Bay, south of Shikoku Island, Japan, for cohorts spawned in February (from Okunishi *et al.*, submitted). Averaged values for each simulation year are thin lines and 9-year averaged values are thick lines in (a, b). Grey belts (a, b) show the range of optimal temperature of feeding for sardine (16–18°C).

less important than physical feedback processes, which is why a one-way flow of information from the climate simulation to the LTLE model is a useful simplification. However, we should also consider these more subtle feedbacks alongside the one-way modeling because large uncertainties remain in the modeling of plankton composition, especially for future projections.

In the modeling of small pelagic fishes such as sardine, anchovy or saury, several significant factors remain to be clarified. One is the grazing effects of top predators such as bigeye tuna, skipjack tuna or yellowfin tuna, and another is the competition for prey plankton among small pelagic fishes. For example, Okunishi *et al.* (2012) pointed out that the predation risk from fish predators, such as skipjack tuna, *Katsuwonus pelami*, which prefer warm water, may increase with warming and that this may cause a reduction in the biomass of Japanese sardine or accelerate the northward shift of sardine migration. Moreover, Japanese sardine seem to compete with other pelagic fish such as Pacific saury for prey plankton (Ito *et al.*, 2007). Therefore, changes in Japanese sardine biomass might reflect the ecosystem structure itself, and the change in structure could feed back to the Japanese sardine. Approaches should be developed to comprehensively couple the many fish-centered food web models that have been developed (as reviewed by Travers *et al.*, 2007) with LTLE models, which can reproduce the heterogeneous distribution of prey. Even though the ecological resolution in the LTLE part of the model is coarse, the multi-species, Individual-based OSMOSE model (Object-oriented Simulator of Marine ecOSystems Exploitation; Shin and Cury, 2001, 2004) coupled with a biogeochemical model, ROMS-NPZD (Regional Ocean Modelling System coupled with a NPZD model; Koné *et al.*, 2005; Machu *et al.*, 2005), is a challenging approach to address this problem. From the perspective of the match-mismatch hypothesis (Cushing, 1990), Cury *et al.* (2008) also pointed out potential effects of changes in: (1) mean relative timing of prey, (2) level of prey abundance, (3) amplitude of year-to-year variations in prey timing in regions where inter-annual variability in temperature is expected to increase. Such effects are important for estimating growth and survival rates in a numerical experiment.

The density-dependent effect of small pelagic fishes is one hypothesis with significant implications for growth and distribution. This is a concept of ideal free distribution that individual behavior, which depends on density-dependent suitability (*i.e.*, higher densities of individuals will lower suitability within habitats), determines the spatial distribution of a group (Myers and Stokes, 1989). As an example, the abundance (fisheries catch) of Japanese sardine was high in the mid 1980s and low in the late 1970s and early 1990s. On the other hand, the inter-annual trend of individual weights of Japanese sardine showed the opposite tendency, with smaller size during the high abundance period of the mid 1980s than during the periods of low abundance. Wada and Kashiwai (1991) also showed a difference in geographical coverage of feeding grounds of Japanese sardine, *i.e.*, broad coverage in the mid 1980s with a high individual growth rate (P/B ratio), and *vice versa* in the late 1970s. These relationships between size, abundance and distribution seem to relate to the density-dependent effect, while these changes are also affected by the bottom-up control associated with changes in the LTLE and physical environment. The density-dependent effect for the expansion of fish distribution associated with increased fish abundance is explained by a conceptual model, "Basin model" (MacCall, 1990). Although it is still difficult to investigate this influence under realistic environmental conditions, even in modeling approaches, explicit two-way approaches, including population dynamics, should be explored in future studies.

The impacts of human activities, such as the overfishing on the HTLE, are considerable problems. Addressing this problem will also require a comprehensive approach, including the effects of fishery changes associated with climate change (*e.g.*, the QUEST-FISH project, funded by the UK Natural Environment Research Council, NERC, has been challenged to estimate the impacts not only on global fisheries resources, but also on the national and regional economies in fishery-dependent areas; Barange *et al.*, 2010). Demands from government for more adequate evaluations of local impacts of climate change on coastal ecosystems are generally increasing. Using the projected physical environment from a high-resolution climate model, we successfully addressed the regional impacts of global warming with eddy-permitting resolution. However, because the horizontal resolutions of most climate models are much coarser (*e.g.*, a few degrees in the ocean components), downscaling approaches, such as the nesting method, will also also be required for addressing the dynamics of coastal ecosystems. Moreover, for simulations of the coastal ecosystem, coupling with regional terrestrial models, including river discharge, may also be significant.

Although we showed an approach for future projection of impacts on marine ecosystems using results of a climate model, many future projections of changes in the physical environment have been reported (IPCC, 2007), and various research groups have taken many different approaches for evaluating impacts on marine ecosystems. In order to reduce uncertainties of projections and to understand the current results and problems, international cooperative efforts like MIPs (Model Intercomparison Projects) would be required for both higher- and lower-trophic level ecosystem modeling. Another significant problem is the shortage of data for plankton biomass, composition and physiological processes, which limits our ability to rigorously test the models.

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3.4 GCM projections of changes to mixed layer depth in the North Pacific Ocean

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Summary

The Working Group on *Evaluation of Climate Change Projections* (WG 20) efforts in determining the General Circulation Model (GCM) projected changes in the mixed layer depth (MLD) in the North Pacific Ocean focused on contributions to the first Terms of Reference. In particular, they were directed at:

A. Analysing and evaluating simulations and projections of the MLD in the North Pacific Ocean using simulations from global climate models submitted to the Intergovernmental Panel on Climate Change (IPCC) for its 4th assessment report.

The results of this analysis are described in a paper by Jang *et al.* (2011) and are summarized in section A below.

B. Changes in the MLD in the equatorial tropical Pacific Ocean and their relation with El Niño Southern Oscillation under climate change projections.

This work is described in a paper by Yeh *et al.* (2009) and summarized in section B below.

A. Changes in the mixed layer depth in the North Pacific Ocean due to global warming and their impact on primary production

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Introduction

This study investigates changes in the mixed layer depth (MLD) in the North Pacific Ocean in response to global warming and their impact on primary production by comparing outputs from 11 models of the Coupled Model Intercomparison Project phase 3 (CMIP3). The ocean mixed layer defines a vertically quasi-homogeneous surface region of temperature, and salinity or density, which directly interacts with the overlying atmosphere. Atmosphere–ocean interaction, therefore, can be modulated by the ocean mixed layer whose depth is determined by wind mechanical stirring, surface buoyancy forcing such as heat flux or freshwater flux, or ocean circulation changes. Changes in MLD, for example, influence the variability of sea surface temperature and oceanic uptake of atmospheric CO_2 (Kraus and Businger, 1995). In addition to air–sea interaction, the MLD also affects phytoplankton dynamics by controlling the availability of nutrients and light and thus, biological productivity in the ocean (Sverdrup, 1953; Yentch, 1990).

Significant changes in the circulation of the ocean or atmosphere have been projected by coupled climate models under global warming (*e.g.*, Lu *et al*., 2007; Vecchi and Soden, 2007; Xie *et al*., 2010). Therefore, the MLD would change in response to the circulation changes under global warming. For example, the deep mixed layers in the Southern Ocean are projected to shoal and shift southward in response to intensified surface warming and poleward shift of the wind field (Sen Gupta *et al*., 2009). The winter MLD is also projected to decrease (Merryfield and Kwon, 2007; Luo *et al*., 2009) in most of the North Pacific Ocean, resulting in a reduction in the formation of mode waters in response to global warming (Luo *et al*., 2009). However, previous studies have focused on either general circulation changes (Sen Gupta *et al*., 2009) or ensemble means rather than individual model simulations (Luo *et al*., 2009). This study investigates both individual model projections and multi-model ensemble changes in the MLD in the North Pacific Ocean due to global warming because multi-model means often hide biases from individual models through the averaging procedure (Lefebvre and Goosse, 2008).

The biological consequences of MLD changes are also of interest because these changes can affect primary production and the timing of spring phytoplankton blooms by altering conditions of nutrients and light. The changes in primary production and timing of seasonal blooms will further affect higher trophic levels. However, it is not easy to predict the changes in primary production, which is controlled by many factors. Primary production consists of two components, regenerated production and new production, fueled by different sources of nutrient inputs (Eppley and Peterson, 1979). Since new production depends on the nutrient inputs from outside of the surface layer, primary production will largely depend on the change in new production. Sources of new production are diverse: upwelling of deep waters, eddies, typhoons, nitrogen fixation, river runoffs, coastal current transportation and aeolian deposits, to name a few. Therefore, to account for all the changes in primary production in the future, all these factors have to be considered. Unfortunately, CMIP3 models do not provide all the information about these factors.

In this study, we will focus on the changes related to seasonal MLD variation based on outputs from 11 CMIP3 models. Typical methods to estimate the future change in primary production are to use ecosystem models coupled to ocean circulation models (*e.g*., Nakata *et al*., 2004, Sarmiento *et al*., 2004; Popova *et al.*, 2006; Hashioka and Yamanaka, 2007). However, ecosystem models with different structures behave differently. If we were to couple several ecosystem models to 11 CMIP3 models and compare the future primary production, a tremendous amount of work would be required, let aside the complications arising in the comparative analysis. Instead, we chose to use the simplest approach of directly estimating primary production from seasonal variation of the MLD. A similar approach was used by Yentch (1990) to estimate new production in the North Atlantic. To estimate the shift in spring bloom timing, we calculated the critical depth based on the Sverdrup model (1953). The simple methods used here may facilitate a robust comparison of 11 model outputs with minimal parameters without the confounding effect of different ecosystem model structures and parameterization.

Data and Methods

CMIP3 models

This study examines the model outputs from CMIP3, as used in the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR4). The outputs from all the CMIP3 models are available from the Program for Climate Model Diagnosis and Intercomparison (PCMDI, archived at http://www-pcmdi.llnl.gov/about/index.php) at the Lawrence Livermore National Laboratory.

For the present climate, we used data from the 20th climate simulation (20th Century Climate in Coupled Models, 20C3M) driven by both anthropogenic and natural forcing. Future projections were also assessed from the same models for the Special Report on Emissions Scenarios (SRES) A1B scenario which assumes moderate future CO_2 emissions. For the analysis, outputs from the last two decades were used for both 20C3M (1980~1999) and SRES A1B (2080~2099) experiments: a 20-year period is believed to be sufficient to account for interannual variability, giving a robust climate (Sen Gupta *et al.*, 2009).

This study analyzes as many models as possible to calculate MLD because we aim to examine individual model simulations, as well as ensemble means, focusing on the differences and similarities of model simulations. Table 3.4.A1 lists 11 out of a total 25 models used in this study, based on the following criteria. First, we removed 6 models with which MLD estimation was not possible: two models (BCC-CM1 and INMCM3.0) were removed simply because temperature and salinity data were not available in the archives. Four models (CCCMA-CGCMT47, CCCMA-CGCMT63, NCAR-PCM1, and UKMO-HadGEM1) were additionally excluded because their first vertical levels start below 10 m depth which is the reference depth used for MLD estimation in this study. Second, we excluded 4 models (GISS-AOM, GISS-EH, GISS-ER, and IAP-FGOALS-g1.0) because they have unrealistic 20th century MLD spatial patterns: the 3 GISS models show a big deep bias exceeding 400 m in the northwestern Pacific area, and IAP-FGOALS-g1.0 has an unrealistically uniform spatial pattern at high latitudes. Third, we further eliminated 4 models (BCCR-BCM2.0, CSIRO-MK3.0, GFDL-CM2.1, and INGV-ECHAM4) whose data were not available from the PCMDI archive for estimation of net heat flux or wind stress. In total, 14 of 25 models were excluded from our analysis.

Although ensemble runs initialized with slightly different conditions are available for some models, just one realization (mostly "run 1") for each model was used for both the 20th and 21st centuries, focusing on multi-model comparison. All the model results were interpolated to a common 2.5° longitude × 2.5° latitude grid where multi-model ensemble means and standard deviations were calculated. To assess model performance in 20th century climate, the simulated MLD from each model was compared with observational estimates by de Boyer Montégut *et al.* (2004; available from http://www.locean-ipsl.upmc.fr/~cdblod/mld.html) which uses the same MLD definition, providing direct comparison between model MLDs and the observation.

This study used the t-test (also known as the Student's t-test; von Storch and Zwiers, 1999) to evaluate the statistical significance of changes in each model and multi-model ensemble means. For the multi-model ensemble mean of 20th century MLD, the t-test estimates its significance under the null hypothesis that each model has the same value as the multi-model mean. For mean changes in each model, significance was calculated by the t-test with unequal variance that states variance of the 21st MLD differs from that of the 20th MLD. A paired t-test (also called "repeated-measures" t-test; von Storch and Zwiers, 1999) was used to check whether the multi-model mean of mean MLD changes is significant or not.

Table 3.4.A1 Coupled GCMs from the CMIP3 used in this study.

No.	Model ID	Ocean model	Oceanic resolution (latitude × longitude, vertical level)	Reference
1	CNRM-CM3	OPA8.1	0.5° - 2° × 2°, L31	Salas Melia (2002)
2	CSIRO-MK3.5	MOM2.2	0.84° × 1.875°, L31	Gordon *et al*. (2002)
3	GFDL-CM2.0	OM3P4	1/3° - 1° × 1°, L50	Delworth *et al*. (2006)
4	IPSL-CM4	OPA	1° - 2° × 2°, L31	Marti *et al*. (2006)
5	MIROC3.2 (hires)	COCO3.3	0.19° × 0.28°, L47	K-1 model developers (2004)
6	MIROC3.2 (medres)	COCO3.3	0.5° - 1.4° × 1.4°, L43	K-1 model developers (2004)
7	MIUB-ECHO-G	HOPE-G	0.5° - 2.8° × 2.8°, L20	Min *et al*. (2005)
8	MPI-ECHAM5	MPI-OM	1.5° × 1.5°, L40	Jungclaus *et al*. (2006)
9	MRI-CGCM2.3.2	Bryan-Cox	0.5° - 2.0° × 2.5°, L23	Yukimoto *et al*. (2001)
10	NCAR-CCSM3	POP	0.27° - 1.1° × 1.1°, L40	Collins *et al*. (2006)
11	UKMO-HadCM3	Bryan-Cox	1.25° × 1.25°, L20	Gordon *et al*. (2000); Johns *et al*. (2003)

Definition of mixed layer depth

Among various methods for MLD estimation, this study utilizes the variable density threshold method (Sprintall and Tomczak, 1992) which considers salinity stratification that is not negligible at high latitudes, as well as temperature effects on stratification. This method defines MLD as the depth where the density increase compared to density at 10 m depth equals an increase in density equivalent to a temperature decrease of 0.2°C. This MLD estimation method has been widely used for various studies, including observational estimation (*e.g.*, de Boyer Montégut *et al.*, 2004) and verification of simulated upper ocean density structure (*e.g.*, Jang and Kang, 2009). Another common method for MLD estimation uses a fixed density criterion which defines MLD as depth where density increase compared to density at 10 m depth equals 0.03 kg m^{-3}. Compared with the fixed density criterion, the criterion used in this study tends to estimate deeper winter MLD by up to 30 m south of 40°N, while estimating shallower winter MLD north of 40°N by up to 30 m.

Entrainment production

After the MLD reaches its minimum in summer, gradual deepening of the mixed layer will entrain nutrients from below. The entrained nutrients are consumed and transformed to organic matter during the course of the year. The amount of nutrients available for primary production in the sun-lit surface layer will depend upon the seasonal excursion of the surface mixed layer. Although seasonal entrainment of nutrients from the deep water might be a major source of new production in the middle latitudes (Yentsch, 1990), there are other sources of nutrients that can be altered under global warming. CMIP3 models do not provide enough information on other sources, such as typhoons, upon which predictions can be built. Therefore, we will focus on seasonal entrainment of nutrients from the deep water and call this portion of new production "entrainment production" to distinguish it from productions due to other sources. Since entrainment production depends on the seasonal excursion of the mixed layer, it will decrease if MLD becomes shallower. In this analysis, we assumed the following. First, only the nutrient supply from entrainment of the deeper water due to seasonal deepening of the surface layer was considered. Other processes such as nitrogen fixation, upwelling related to eddies and typhoons, and atmospheric inputs were not considered. Second, all the nutrients entrained into the surface layer is transformed to organic carbon during the year. Third, nitrogen is considered the major limiting nutrient and only nitrate is considered in calculating primary production.

We calculated entrainment production at 4 × 10 grid cells in the Kuroshio Extension (KE) region (Fig. 3.4.A1). The cells are spaced in a 30.5–39.5°N and 151.5–178.5°E rectangle at an interval of 3°. The following equations were used to estimate entrainment production from the nitrogen entrained from deepening of the mixed layer.

$$PN\,(\mathrm{mol\,m^{-2}}) = \int_{z=\mathrm{MLD_{min}}}^{z=\mathrm{MLD_{max}}} N(z)\,dz$$

$$PP\,(\mathrm{gC\,m^{-2}\,yr^{-1}}) = PN \cdot 12 \cdot \frac{C}{N}$$

Here, *PN* stands for the depth-integrated nitrogen entrained by deepening of the mixed layer (summer to winter). $\mathrm{MLD_{max}}$ and $\mathrm{MLD_{min}}$ are annual maximum and annual minimum of MLD, respectively. These values are determined from monthly density profiles from each CMIP3 model for every grid cell. $N(z)$ is the vertical profile of nitrate when the MLD is at its annual minimum (*i.e.*, summer) and *PP* is the annual entrainment production expressed in carbon and is obtained from *PN* by multiplying by the Redfield ratio and carbon atomic mass. To estimate $N(z)$ at each grid cell, monthly climatologies (1° grid) of nitrate were derived from the on-line version of the World Ocean Atlas 2009 (Garcia *et al.*, 2010; available at http://www.nodc.noaa.gov/OC5/WOA05/pr_woa09.html). At each grid cell, nitrate profiles were obtained from standard depths (0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, 500 m). The density profiles from each grid cell were examined and the month of minimum MLD was chosen to select the nitrate profile. Figure 3.4.A2 shows an example of nitrate profiles that are used for calculating the entrainment production for CSRIO-MK3.5. The profiles are from the months when the MLDs reach their minimum at each grid point. Since the time of minimum MLD can be different depending on the model and location, the pattern of nitrate profiles can be different for each model. The same climatology of nitrate profiles is used for the future assuming the changes in the profile would be relatively small when nitrate is integrated through depth.

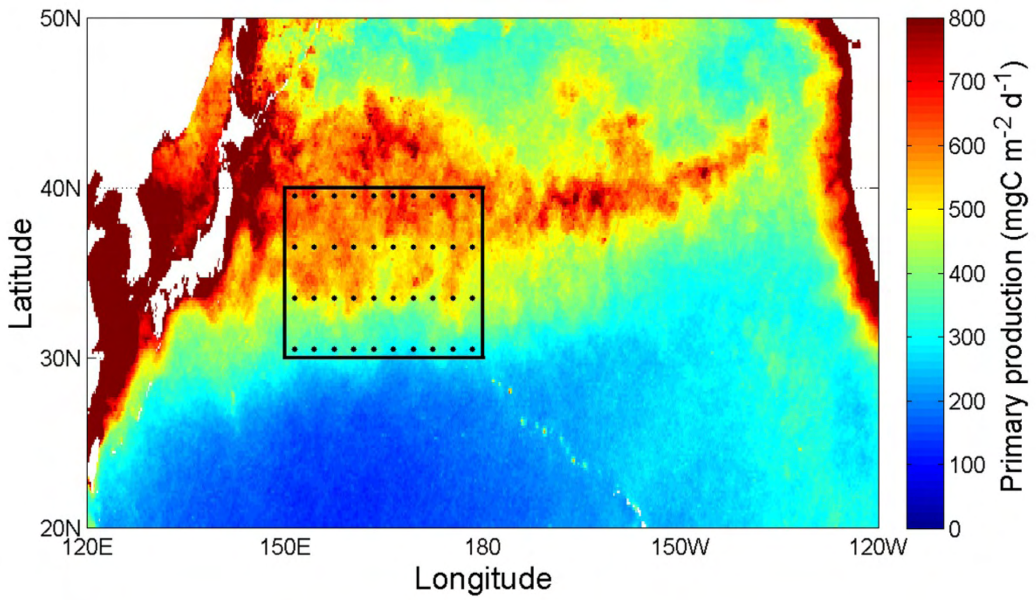

Fig. 3.4.A1 Location of the grid cells (4 × 10 cells at an interval of 3°) where entrainment production and spring bloom timing are calculated. The background image is the average daily primary production in 1999 estimated by the Vertically Generalized Production Model (VGPM; http://www.science.oregonstate.edu/ocean.productivity/).

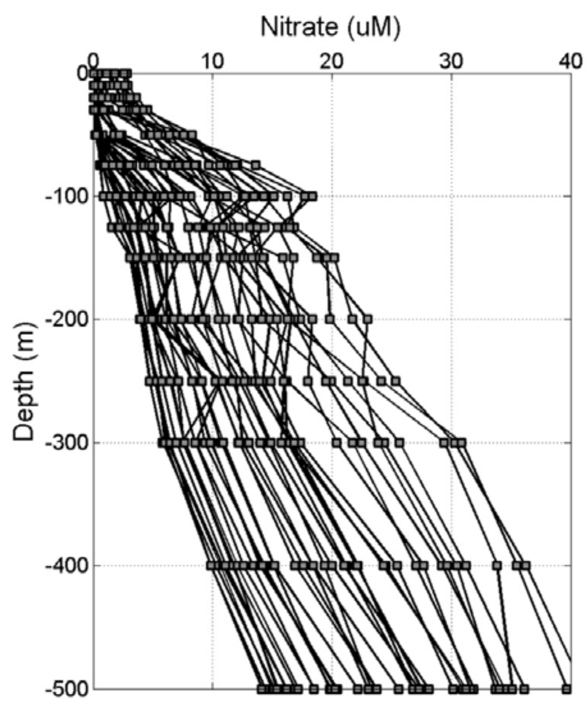

Fig. 3.4.A2 An example of nitrate profiles used to calculate the entrainment production (in this case for CSRIO-MK3.5). The profiles are selected from monthly climatology of the World Ocean Atlas (Garcia *et al*., 2010) for the months when the mixed layer depths (MLDs) reach their minimum at 4 × 10 grid points.

Timing of spring bloom initiation

The timing of spring bloom initiation was calculated at the same grid cells as with entrained production (Fig. 3.4.A1). As a proxy of the timing of the seasonal bloom initiation, we calculated the time when the MLD becomes shallower than the critical depth according to the concept first proposed by Sverdrup (1953). The exact calculation was made following the formulation of Nelson and Smith (1991),

$$Z_c = \frac{\sum I_o}{3.78 \cdot K_{PAR}}.$$

Here, Z_c is the critical depth, ΣI_o is daily integrated PAR (Photosynthetically Active Radiation), and K_{PAR} is the diffuse attenuation coefficient of PAR downward in the water column. Above surface PAR was calculated by multiplying 0.45 (Baker and Frouin, 1987) to the shortwave radiation data from each CMIP3 model. K_{PAR} was taken from Jerlov (1976). To estimate the exact timing when the MLD becomes equal to Z_c, linear interpolation was made on the monthly time series of the MLD and critical depth with a precision of one decimal. Figure 3.4.A3 illustrates this procedure for two different cases.

Results

Winter MLD in the present climate and its projected change

In the North Pacific, winter mixing of the surface layers controls the amount of nutrients entrained into the upper ocean which supports phytoplankton growth. In addition, the winter mixing is essential to the formation of the mode waters that determine the property of the thermocline water and connect the upper ocean to the deep ocean (Hanawa and Talley, 2001). Therefore, this study investigates the winter MLD averaged over January, February, and March.

The observed winter MLD presents significant spatial variations north of 25°N, while it is nearly uniform south of 25°N (Fig. 3.4.A4, the last panel). The deepest MLDs exceeding 200 m are found between 25°N and 40°N in the western North Pacific. The observed winter MLD features three local maxima exceeding 125 m: the first in the eastern subtropical Pacific centered at 140°W and 30°N, the second and third in the Northwest Pacific. All three deep mixed layers are associated with mode water formation. The first local maximum corresponds to the region where eastern subtropical mode water (ESTMW) forms (Hosoda *et al.*, 2001). The second, centered near 150°E and 32°N, is associated with subtropical mode water (STMW), and the third, near 180° and 40°N, is related with central mode water (CMW).

Most models simulate a large MLD in the ESTMW region, with slightly different values and locations, except MIUB-ECHO-G and MRI-CGCM2.3.2 which show no distinct local maximum. On the other hand, the other two maxima tend to coalesce into one large region in the KE in most models, which is due to overshooting of the Kuroshio in the low-resolution models (Thompson and Cheng, 2008), while MIROC3.2 (hires) and MPI-ECHAM5 have a distinct signature for the two maxima with different locations. Moreover, the simulated deep mixed layers in the KE are overestimated by 50 m (CSIRO-MK3.5) ~ 380 m (GFDL-CM2.0) compared with the observation. This deep bias in the KE is probably due to underestimation of the Kuroshio which carries less heat into the KE region and thus less stratification, giving a deep MLD bias there (Thompson and Cheng, 2008).

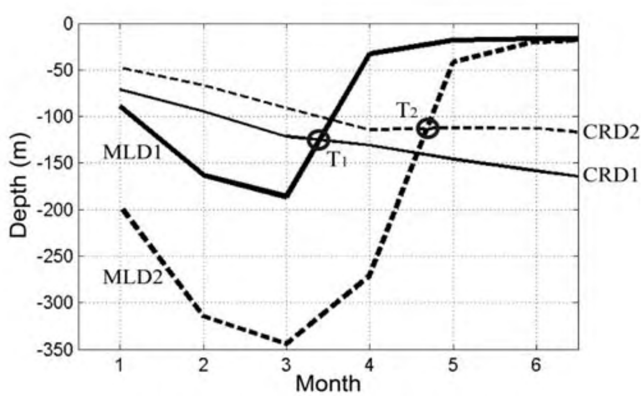

Fig. 3.4.A3 An example of seasonal changes in mixed layer depth (solid lines) and critical depth (broken lines). The intersections, T1 and T2, represent the timing of spring bloom initiation.

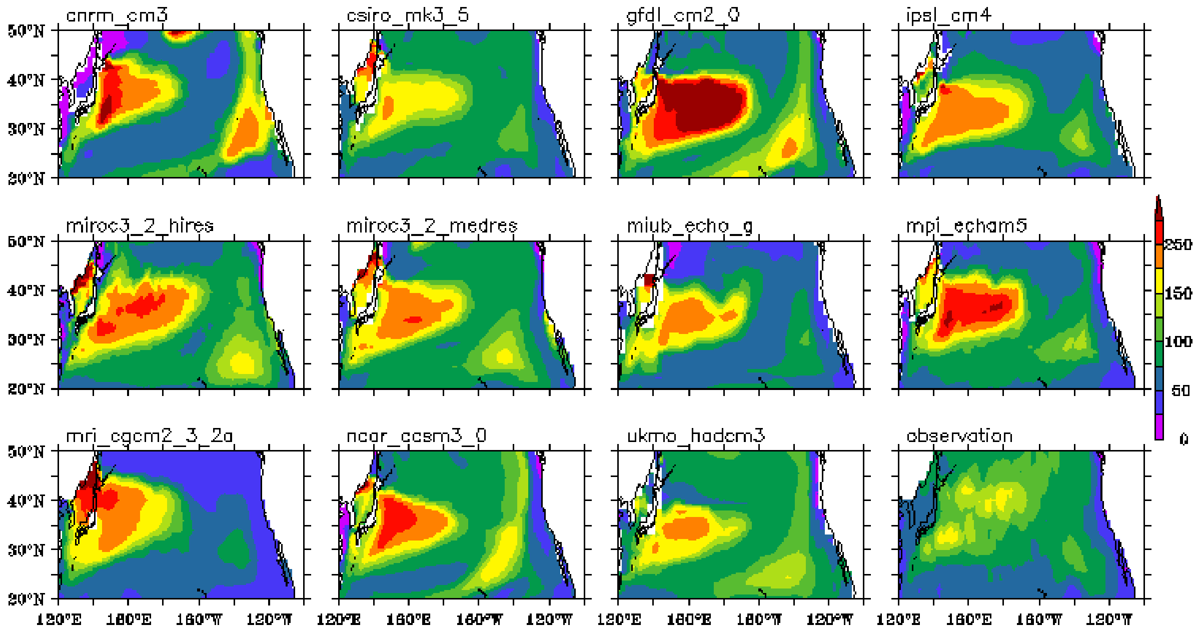

Fig. 3.4.A4 Winter (DJF) mixed layer depth (MLD, in m) in the 20th century climate from 11 CMIP3 models and observational estimate (last panel). The observational MLD is from the climatology data by de Boyer Montégut *et al*. (2004; available from http://www.locean-ipsl.upmc.fr/~cdblod/mld.html). The shading intervals are 25 m from 0 to 150 m, and 50 m for larger values.

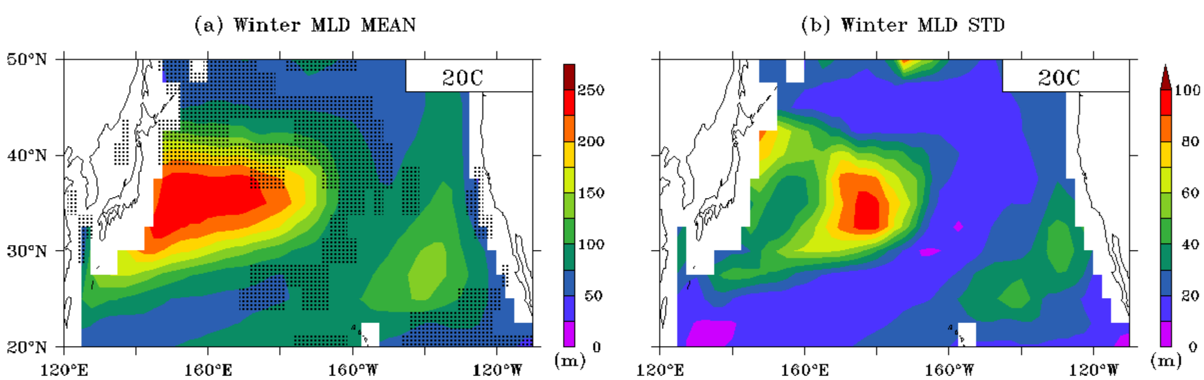

Fig. 3.4.A5 Winter (JFM) mixed layer depth (m) in the 20th century climate: (a) multi-model mean and (b) multi-model standard deviation. For multi-model mean, the regions statistically insignificant at 95% level are stippled.

Multi-model mean MLD (Fig. 3.4.A5a) reflects well the general features in individual models: deep MLD in the KE and in the ESTMW formation region. It also carries the common MLD biases from individual models: a deep bias and one deep larger MLD region rather than the observed two localized maxima in the KE, which is inherent from low resolution in most of the CMIP3 models.

Significant inter-model differences (greater than 90 m) are observed in the mid-latitude between 160°E~160°W and 30°~40°N, with its maximum exceeding 110 m centered at 180°, 32°N (Fig. 3.4.A5b). A deep mixed layer (> 300 m) extends to the east of 180° longitude in some models, including GFDL-CM2.0, while it is limited west of 180° longitude in the models, including NCAR-CCSM3 and UKMO-HadCM3, resulting in a dominant inter-model variability near 180° longitude. The largest inter-model MLD difference roughly corresponds to the region of the largest inter-model variability of the wind stress (not shown). This implies that a large component of inter-model MLD difference results from a different wind stress in each model.

MLD in the 21st century decreases in most regions of the North Pacific, while the spatial distribution of the MLD is nearly unchanged (Figs. 3.4.A6 and 3.4.A7). The overall shoaling results largely from intensified upper-ocean stratification caused by amplified surface warming and freshening (Luo *et al.*, 2009).

Significant MLD decreases (> 30 m) are found in two regions: one in the KE, and the other in the region centered at 140°W and 30°N. The consistent shoaling of the mixed layer in the KE roughly matches with the region of significantly weakened wind stress (Fig. 3.4.A8a), implying that the decreased MLD in the KE is mainly attributable to the weakened wind stress over the KE. In association with reduced wind, latent cooling is reduced, resulting in diminished net surface cooling in the KE (Fig. 3.4.A8b). This additionally helps reduce MLD in the KE.

On the other hand, the MLD increases in the narrow-banded region between 40°~45°N and west of 160°W, just north of the KE front. This deepening is largely driven by a northward shift of the KE rather than by intensification of surface cooling or wind mixing. In the multi-model means (Fig. 3.4.A8), the surface cooling is projected to be weakened and the wind intensifies slightly which cannot significantly contribute to the deepening.

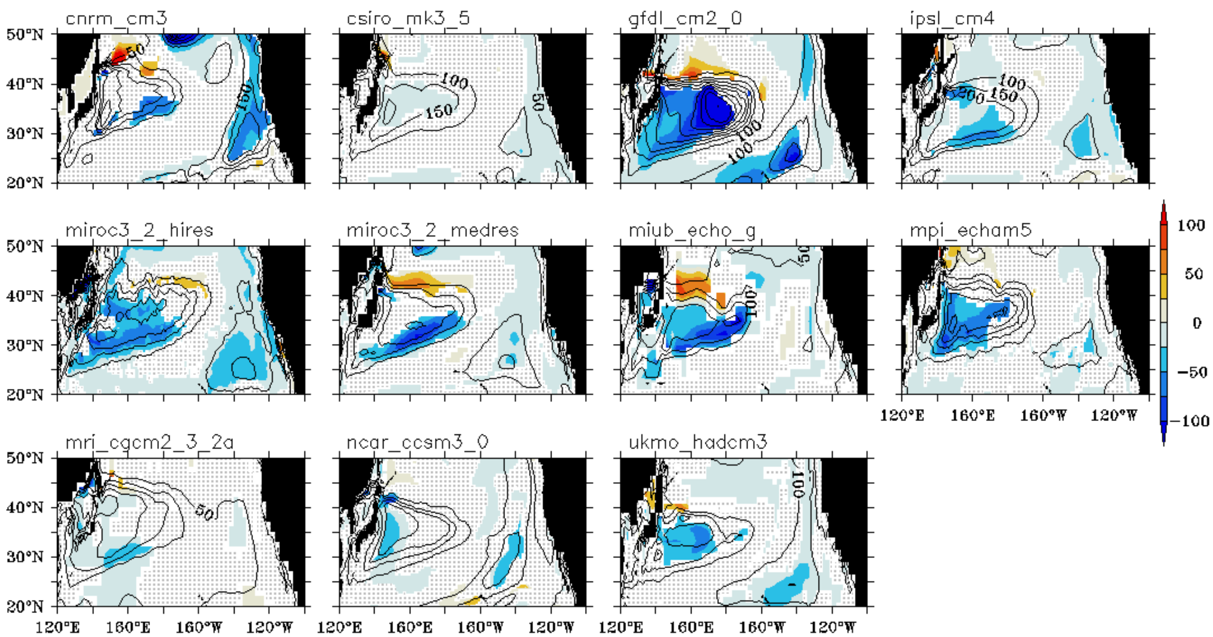

Fig. 3.4.A6 Projected winter (JFM) mixed layer depth (MLD, in m) changes (colors) in future climate (SRES A1B) for each model. Negative (positive) values in blue (red) color indicate MLD shoaling (deepening) in future climate. Superimposed is the present climate (20C3M) MLD (contour interval: 50 m). The regions statistically insignificant at 95% level are stippled.

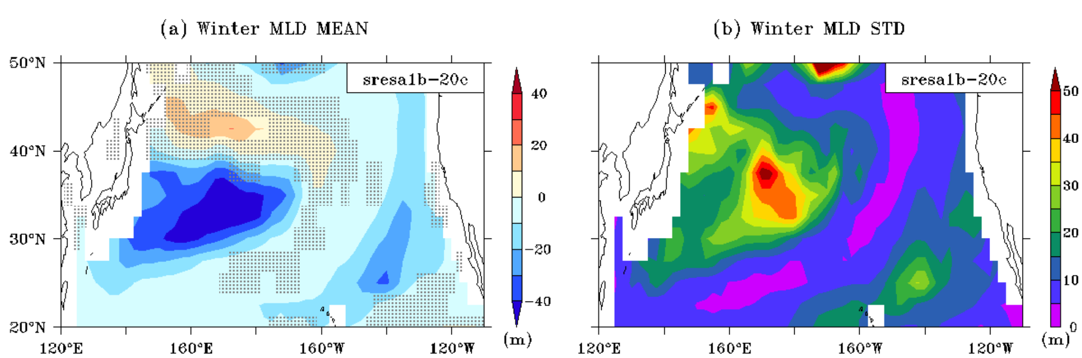

Fig. 3.4.A7 Projected changes (21C–20C) in the winter (JFM) mixed layer depth (MLD, in m): (a) multi-model mean, and (b) multi-model standard deviation. For multi-model mean, the regions statistically insignificant at 95% level are stippled.

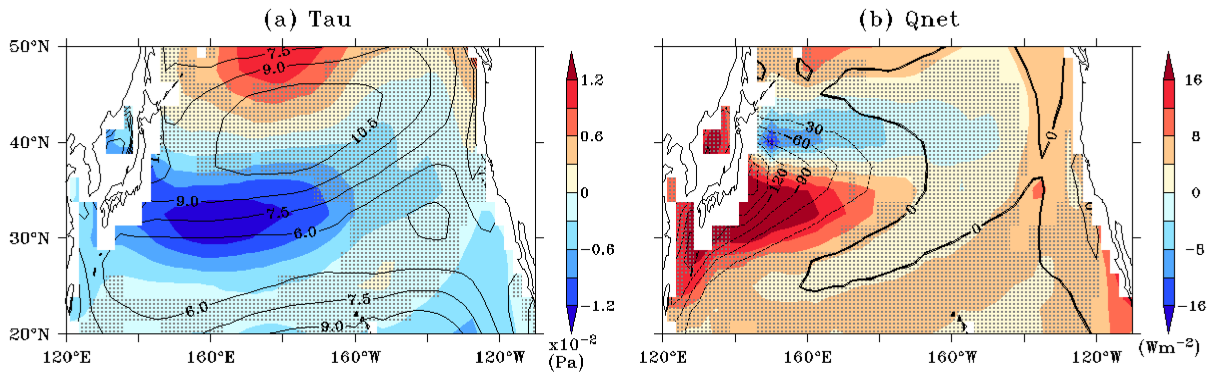

Fig. 3.4.A8 Projected changes (21C–20C) in the long-term multi-model means: (a) surface wind stress (Pa), and (b) net heat flux (Wm^{-2}). Superimposed contour lines are the present climate (20C3M) values. Negative values in net heat flux indicate cooling of the ocean. The regions statistically insignificant at 95% level are stippled.

Future primary production changes

We estimated the annual entrainment production at each of 4 × 10 grid cells (Fig. 3.4.A1) for 20C and 21C and calculated the percent change of the annual entrainment production of 21C to that of 20C for each of the11 CMIP3 models. In Figure 3.4.A9, boxplots of the percent changes from each model are shown along the four latitudes (see Figure 3.4.A1 for locations). The overall trend is that the entrainment production will decrease more towards the south (Fig. 3.4.A9). This trend is particularly pronounced with the models 5, 6, 7, 8, 9, and 11 (MIROC3.2 (hires), MIROC3.2 (medres), MIUB-ECHO-G, MPI-ECHAM5, MRI-CGCM2.3.2, and UKMO-HadCM3). Model 7 (MIUB-ECHO-G) shows the largest percent change of decrease (median = –74.5%) along 30.5°N. On the other hand, model 1 (CNRM-CM3) shows the largest decrease (median = –50.9%) in the middle latitudes. Models 2 and 10 (CSIRO-MK3.5 and NCAR-CCSM3) show small decreases (<15%) at all the latitudes. Models 7 and 11 (MIUB-ECHO-G and UKMO-HadCM3) show large decreases along 30.5°N but very large increases (median = +55.5% and +118.3%, respectively) along 39.5°N. When all the grid cells are pooled, median values of the percent change range from –10.6% (MRI-CGCM2.3.2) to –40.6% (GFDL-CM2.0). The largest percent decreases range from –40.0% (CSIRO-MK3.5) to –92.2% (MIUB-ECHO-G). The largest percent increases range from –4.0% (IPSL-CM4) to 311.6% (UKMO-HadCM3).

Estimated time of spring bloom initiation, as approximated by crossing time of MLD and critical depth, shows a similar trend with the entrainment production (Fig. 3.4.A10). Blooms initiate earlier towards the south with models 5, 6, 7, 8 (MIROC3.2 (hires), MIROC3.2 (medres), MIUB-ECHO-G, and MPI-ECHAM5). On the other hand, blooms initiate along 39.5°N with models 4 and 10 (IPSL-CM4 and NCAR-CCSM3). Models 7 and 11 (MIUB-ECHO-G and UKMO-HadCM3) show delayed spring blooms along 39.5°N. Thus models 7 and 11 (MIUB-ECHO-G and UKMO-HadCM3) show a very wide range of bloom timing shift (–3.2 to +2.4 weeks in model 7 and –1.5 to +2.9 weeks in model 11; negative values indicate advancement of bloom timing, positive delay). For all the grid cells combined, median values of the timing shift range from 0.0 (MRI-CGCM2.3.2) to –1.7 weeks (MRI-CGCM2.3.2). Minimum values range from –0.9 (NCAR-CCSM3) to –5.7 weeks (MIROC3.2 (medres)). Maximum values range from 0.0 (NCAR-CCSM3) to +5.1 weeks (UKMO-HadCM3).

To summarize, the overall trend is that the spring blooms initiate early but actual values differ very much, depending on the model and location. Similarly with entrainment production changes, some models show advancement in spring bloom initiation in all the areas while some models show mixed differences in differing magnitudes.

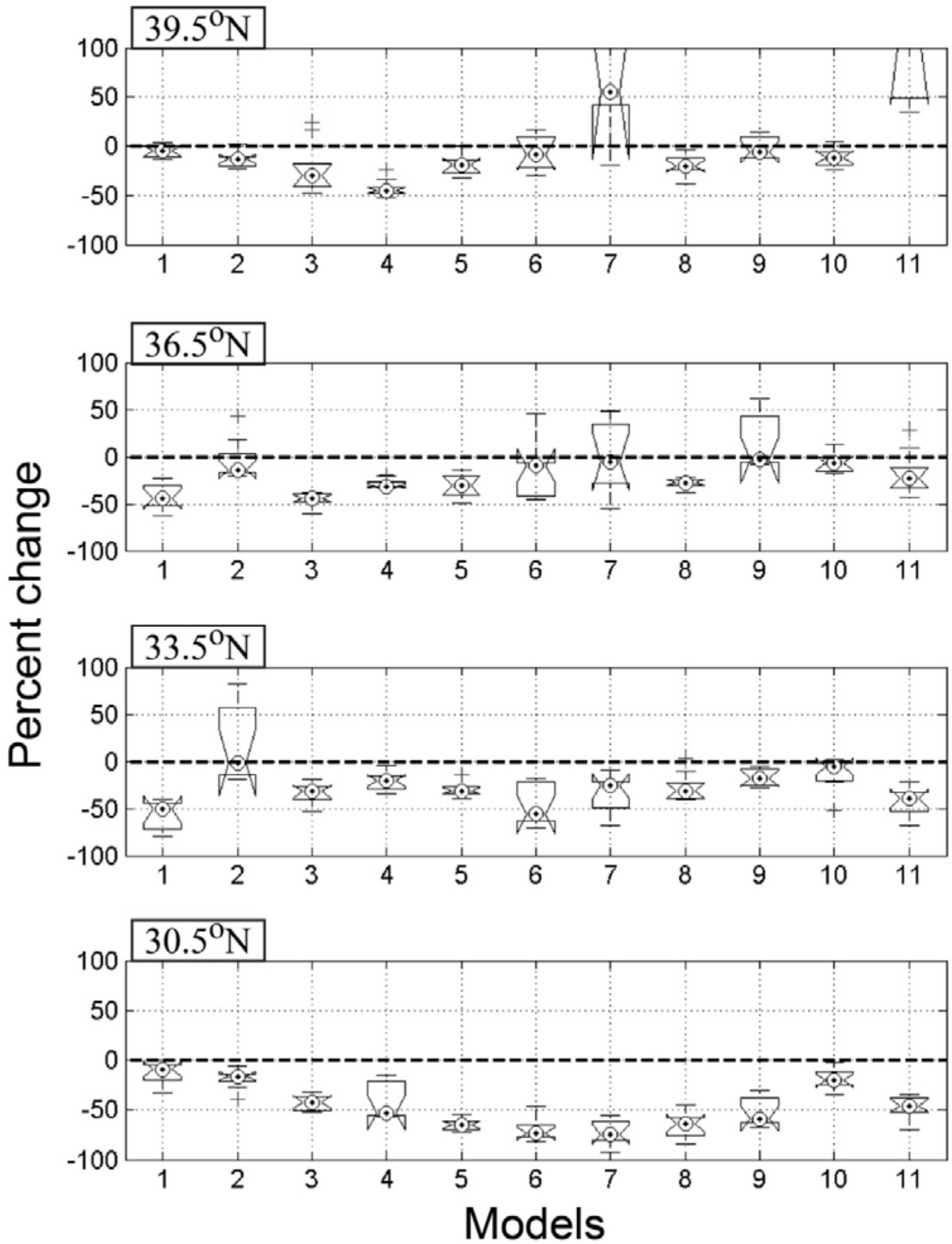

Fig. 3.4.A9 Predicted percent change in entrainment production by 11 CMIP3 models. Model number represents 1: CNRM-CM3, 2: CSIRO-MK3.5, 3: GFDL-CM2.0, 4: IPSL-CM4, 5: MIROC3.2 (hires), 6: MIROC3.2 (medres), 7: MIUB-ECHO-G, 8: MPI-ECHAM5, 9: MRI-CGCM2.3.2, 10: NCAR-CCSM3, and 11: UKMO-HadCM3 (see Table 3.4.A1). Dots in the circles represent the median, boxes delimit the 25th and 75th percentiles and crosses represent outliers.

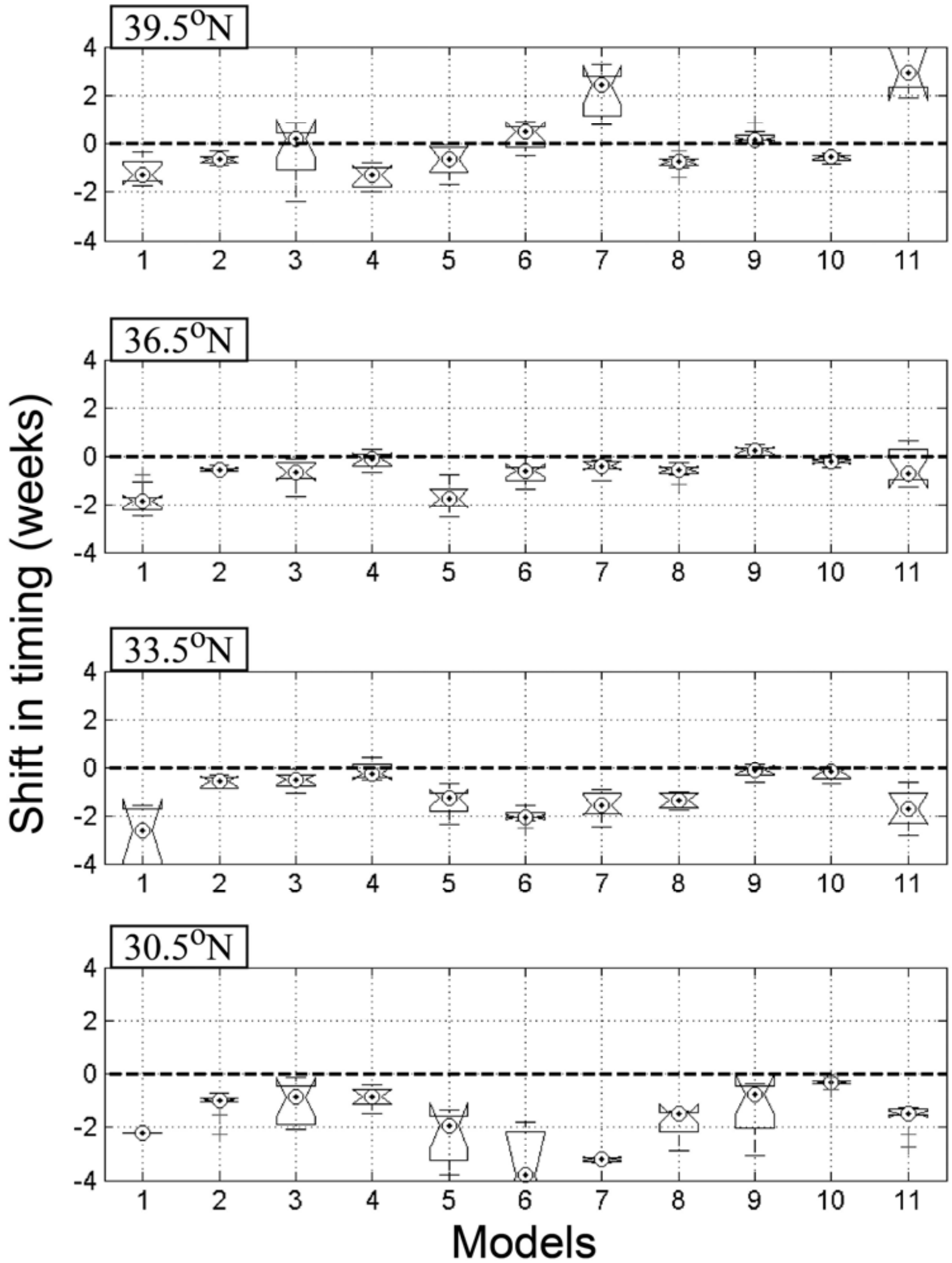

Fig. 3.4.A10 Predicted shift in spring bloom initiation by 11 CMIP3 models. Model numbers as in Figure 3.4.A9 (see also Table 3.4.A1). Dots in the circles represent the median, boxes delimit the 25th and 75th percentiles and crosses represent outliers.

Discussion

Despite significant differences in model configurations (*e.g.*, resolution or subgrid-scale parameterization), most of the CMIP3 models used in this study project a consistent shoaling of the mixed layer in the KE, mainly driven by a consistent weakening of wind stress and the associated reduction in surface cooling over the KE. One might argue that most CMIP3 models analyzed are not resolving meso-scale eddies that could be crucial for simulating the Kuroshio and its extension, and thus mixed layer depth, and their future changes. Noting that a consistent decrease in the KE is also projected in the MIROC3.2 (hires) model, with the highest model resolution among the CMIP3 models, it is not likely that model resolution could change the essential aspects of MLD projection in the KE, at least qualitatively.

We have shown decreases in entrainment production and hence primary production in the 21st century in all the 11 CMIP3 models. We now examine whether the method used here to determine entrainment production from the seasonal changes in MLD is reasonable. We chose to use satellite-based primary production estimates as an independent comparison. Since most of the CMIP3 models overestimate MLD when compared with observed data, the resultant entrainment production will be overestimated accordingly. Therefore, we chose model 2 (CSIRO-MK3.5, Table 3.4.A1), which shows the least overestimation, for comparison with the satellite-based estimates. The satellite-based primary production was obtained from Oregon State University (http://www.science.oregonstate.edu/ocean.productivity/). The satellite data used are by SeaWiFS (Sea-viewing Wide Field-of-view Sensor) which are available only for the period of 1997–2008. We compared the entrainment production calculated from MLD changes for 1998 (July 1998 to June 1999) and 1999 (July 1999 to June 2000) with satellite-based primary production in the same periods at the grid cells.

There is a good relationship between the total primary production and entrainment production estimated from annual changes in MLD in the study area (Fig. 3.4.A11). MLD-based estimates of entrainment production account for 81.8% of the variance in total primary production of the study region, which includes oligotrophic to moderately-productive areas. We do not expect a quantitatively accurate relationship between the two because of the uncertainties in MLD estimates, nitrate profiles and satellite estimation of primary production. In Figure 3.4.A11, new production is estimated by multiplying the *f*-ratio (Eppley and Peterson, 1979) to the satellite primary production and is denoted by a broken line. When primary production is below approximately 180 gC m^{-2} yr^{-1}, entrainment production estimates fall below the new production line. Above 180 gC m^{-2} yr^{-1}, there are more overestimates. This is because the MLD projected by model 2 (CSIRO-MK3.5) overestimates in the north and underestimates in the south. Despite this systematic difference, the coherent relationship between entrainment production and satellite primary production suggests that MLD-based estimation of entrainment production can be applied to the MLD outputs of other CMIP3 models.

The results of this analysis indicate that 11 CMIP3 models give a wide range of differences. Despite the similar overall trends, the magnitude of changes in primary production and timing of spring blooms were quite different, depending on models and latitudes. Hashioka and Yamanaka (2007) made projections on the ecosystem changes in the western North Pacific using a high resolution 3D ecosystem–biogeochemical model. Their results were different from the results of this study in that change in primary production was smaller but advancement of spring bloom was larger.

Yentch (1990) estimated new production from monthly nitrate profiles and concluded the estimates were reasonable compared to the observed values in the North Atlantic. Although entrainment of deep nutrients may be the major source of primary production in the KE, we recognize other factors are also important and we differentiate entrainment production from new production. In the KE region, eddies, typhoons, and nitrogen fixation may also be important contributions to new production in addition to the changes in entrainment production.

Increases in water temperature and carbon dioxide can change new production in the future in the study area. We examine whether the increased temperature or carbon dioxide can enhance new production significantly. The first possibility is that increased temperature can enhance nitrogen fixation. Thus far, we only considered nitrate assimilation as sources of new production but nitrogen fixation could be potentially important in the new production in the subtropical North Pacific (Karl *et al.*, 1997; Dore *et al.*, 2002; Capone *et al.*, 2005; Kitajima *et al.*, 2009). Nitrogen is fixed by diazotrophs such as *Trichodesmium*, which are broadly distributed in oligotrophic, tropical, and subtropical oceans (Capone *et al.*, 1997). Nitrogen fixation by *Trichodesmium* corresponds to half or more of the upward nitrate flux (at Station ALOHA; western subtropical and tropical North Atlantic) and accounts for up to 47% of the primary production in the tropical North Atlantic Ocean (Carpenter *et al.*, 2004).

Two questions are raised in considering the possibility of an increase in nitrogen fixation in 21C. The first is whether the range of temperature increase projected by the models can enhance the new production significantly. Maximum specific growth rates of the axenic *Trichodesmium* IMS-101 strain were highest in the temperature range between 24–30°C, with a peak at 27°C (Breitbarth *et al.*, 2007). Hence if the temperature increases towards the optimal value, nitrogen fixation can increase. However, small changes in temperature (4°C) did not appear to affect gross nitrogen fixation in cultures of *Trichodesmium* IMS101 (Mulholland and Bernhardt, 2005; Hutchins *et al.*, 2007). The temperature increase from the models ranges from 2.2–3.3°C (annual means) and 1.9–4.0°C (annual maximum). Therefore, the projected temperature increases may not lead to a significant increase in nitrogen fixation.

The second question is whether the temperature increase alone can enhance the new production significantly. Studies have shown that nitrogen fixation can be limited by iron (Raven, 1988; Rueter *et al.*, 1990; Falkowski, 1997) and by phosphorus (Wu *et al.*, 2000; Sañudo-Wilhelmy *et al.*, 2001; Moutin *et al.*, 2005; Mulholland and Bernhardt, 2005; Kitajima *et al.*, 2009). Mahaffey *et al.* (2005) further argued that nitrogen fixation activity is primarily regulated by iron and/or phosphorus availability. The study of Kitajima *et al.* (2009) in the western North Pacific supports this view. The whole-water nitrogen fixation was markedly elevated in winter throughout the study area compared to that in summer, probably due to the increased upward supply of phosphate as a result of a deeper mixed layer in winter (Kitajima *et al.*, 2009). In a similar vein, the effects of increased carbon dioxide on nitrogen fixation can be evaluated. Hutchins *et al.* (2007) reported that chlorophyll-*a* normalized nitrogen fixation rates of Pacific and Atlantic isolates increased 35 to 100% at projected carbon dioxide levels of the year 2100 (76 Pa, 750 ppm), even under severely P-limited steady-state growth conditions, relative to present day carbon dioxide conditions. Whether this can be extended to a longer time scale (such as annual growth) is questionable, as nitrogen fixation will eventually be limited by iron and/or phosphorus availability.

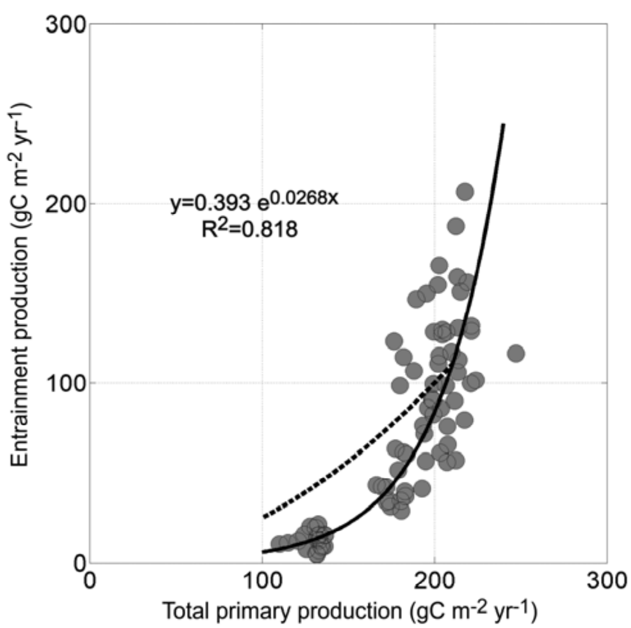

Fig. 3.4.A11 The relationship between the annual primary production (by the Vertically Generalized Production Model ,VGPM) and entrainment production (by the model CSIRO-MK3.5) at the grid cells (see Fig. 3.4.A1) during 1998 and 1999. N = 80. The broken line represents the new production estimated from the *f*-ratio by Eppley and Peterson (1979).

Although CMIP3 models do not provide data to evaluate the impacts of future changes in typhoons and eddies on primary production, eddies (Kimura *et al*., 2000) and typhoons (Siswanto *et al*., 2007) can contribute to the new production in the western North Pacific. Therefore, it is desirable to evaluate other sources of new production.

Conclusions

This study finds consistent mixed layer depth (MLD) changes in the future in the North Pacific Ocean from all the 11 CMIP3 models: a shoaling in the Kuroshio Extension (KE) region and a deepening north of the Kuroshio Front. The shoaling is attributable to the weakening in wind stress and the associated decrease in ocean cooling in the KE, while the deepening is mainly driven by the northward shift of the KE. However, the detailed structures and magnitudes in the MLD changes are substantially different across the models, reflecting significantly different model configurations including model resolutions, sub-grid mixing parameterization, and model physics. The differences are accordingly reflected in primary production on local scales.

The entrained production, which may be the major component of primary production in the region, was estimated based on MLD changes in the KE. The entrainment production in the KE in 21C will be decreased by 10.7~40.3% (range of 11 median values) and spring blooms will occur 0.0~1.7 week (range of 11 median values) earlier in response to the changes in MLD in the KE region. Despite the overall trends, the magnitude of changes in primary production and timing of spring blooms were quite different, depending on models and latitudes.

The above findings suggest that the CMIP3 projected changes in the MLD and related changes in primary production in the North Pacific are quantitatively very different, although they are qualitatively agreeable. To clarify the causes of the differences is necessary at least for some models provided with detailed information, and is planned as a future research theme.

B. Changes in the MLD in the equatorial tropical Pacific Ocean and their relation with ENSO under climate change projections

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Introduction

The mixed layer is the ocean surface zone that responds most quickly and directly to atmospheric fluxes, and it is through the mixed layer that heat and momentum fluxes are transmitted to the deeper ocean and generate longer timescales of variability. Therefore, the ocean's mixed layer depth (hereafter referred to as MLD) is one of the most important quantities in the upper ocean, and is closely associated with physical, chemical and biological systems (Fasham, 1995; Kara *et al*., 2003). MLD variability dominates on several short-term timescales, *i.e.*, diurnal, intra-seasonal, and seasonal (McCreary *et al*., 2001). However, recent studies of long-term observation records have suggested that the MLD undergoes low-frequency changes in the North Pacific and Atlantic Oceans (Carton *et al*., 2008). In addition, a number of studies have reported a long-term trend in MLD (Polovina *et al*., 1995; Chepurin and Carton, 2002; Carton *et al*., 2008). Such low-frequency variability and the shallowing or deepening trend in the MLD over the past few decades have raised the question of whether, and how, human-induced 'greenhouse' warming impacts MLD variability.

The variability of the MLD under global warming would determine a physical environment in the upper ocean that could affect ocean–atmosphere interactions, ocean physics and upper ocean productivity (Pierce, 2004). In particular, as the site of significant climate variability, the MLD closely links the dynamics and thermodynamics of the upper layers in the tropical Pacific and, as such, is likely to be a key parameter for understanding the response of the tropical Pacific climate system to global warming. In spite of a large number of studies on the influence of climate change using Coupled General Circulation Models (CGCMs) (see http://www-pcmdi.llnl.gov/ipcc/subproject_publications.php), there has been little investigation of changes in MLD under climate change projections. We examine changes in MLD under atmospheric CO_2 doubling in two different CGCMs, focusing on changes in MLD in the tropical Pacific. Furthermore, we examine changes in the relationship between the MLD and El Niño–Southern Oscillation (ENSO) under increased greenhouse gases. Indeed, the variability associated with heat storage or release in the mixed layer is quite diverse due to competition between the equatorial waves and the direct heat flux forcing in the tropical Pacific. This balance is likely to be sensitive to the environmental conditions in a way that depends on MLD characteristics. More generally, since the MLD determines the heat capacity of the ocean, it has a strong impact on air–sea exchanges, and therefore on ENSO, which includes its teleconnections (Sui *et al*., 2005). For these reasons it is worthwhile examining changes in the MLD–ENSO relationship under increased CO_2 concentrations. In order to analyze changes in the MLD under atmospheric CO_2 doubling, we examined two CGCMs: a control simulation using pre-industrial greenhouse gas concentrations and an experiment simulation using doubled CO_2 levels.

Model and Methodology

We used selected CGCM simulations, namely, MRI-CGCM2.3.2a and GFDL-CM2_0 (hereafter referred to as MRI and GFDL). The CGCM simulations were made available by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) on the website http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php. In this study, the MLD was obtained from Monterey and Levitus (1997) and Suga *et al*. (2004) based on the depth where the density differs from the surface density by 0.125 kg m^{-3}. We chose a density difference criterion because salinity also contributes to the density variation significantly in the tropical Pacific. Note that small change of the surface density criteria leads to slight differences in the estimation of MLD but the overall results are unchanged. The terms "control experiment" and "2xCO2 experiment" refer to data from the last 100 years for the control experiment and the 2xCO2 experiment, respectively.

MLD in the Control Experiment

Prior to showing the MLD simulated in the CGCMs, we begin by showing the climatological annual mean MLD in observations. Figure 3.4.B1a shows the climatological mean MLD in the tropical Pacific calculated from the Levitus data (Levitus, 1982). Mean MLD ranges from 20 to 80 m in the tropical Pacific. A shallow MLD is found in the eastern tropical Pacific, which is associated with a shallow thermocline depth in the same region (Yu and McPhaden, 1999). In the central equatorial Pacific the spatial structure of the mean MLD is characterized by a pair of deep MLDs off the equator in both hemispheres, which is similar to the results obtained by Kara *et al*. (2003) and de Boyer Montegut *et al*. (2004) in spite of different definitions of MLD. Using the data from the World Ocean Database 2005 archive for the period 1960–2004, Carton *et al*. (2008) showed that the climatological maximum MLD may exceed 75 m in the central tropical Pacific basin, decreasing to less than 40 m in the east, which is also generally consistent with Figure 3.4.B1a. A deep MLD in the central equatorial Pacific could be associated with significant vertical turbulent kinetic energy due to strong zonal wind stress over this zone (Garwood *et al*., 1985). On the other hand, upwelling at the equator drags up the thermocline, and thus causes the decrease in MLD compared to the off-equatorial region, although it is not clearly observed in the climatological data of low resolution (Noh *et al*., 2005). The MLD pattern is also associated with equatorial wave dynamics. Strong zonal wind stress in the central equatorial Pacific (Wittenberg, 2004) produces strong upwelling off the equator in both hemispheres. This is mainly due to an Ekman pumping by wind stress curl off the equator in both hemispheres (Kessler, 2006), resulting in a deep MLD through active mixing processes, as seen in Figure 3.4.B1a. On the other hand, an Ekman pumping continuously forces a Rossby wave propagating to the west (Qu *et al*., 2008); therefore, the variability of the MLD is closely associated with equatorial wave dynamics in the central equatorial Pacific from the forcing region, in particular the annual equatorial Rossby wave in which its maximum center is located off the equator (Kessler and McCreary, 1999) or the tropical instability wave activity that can also rectify the background state.

Figure 3.4.B1b and c is the same as Figure 3.4.B1a but relates to the control experiments in the MRI model and the GFDL model, respectively. The spatial structure of the mean MLD simulated in both the MRI model and the GFDL model is dominated by a pair of deep MLDs which are at a maximum off the equator in the western and central equatorial Pacific, which is in agreement with the observations. However, the pattern is much more symmetric towards the equator, suggesting that equatorial Rossby waves have a greater impact on MLD variability in the CGCMs than in the observations. In addition, the mean MLD simulated in the MRI model is shallow, below 50 m, along the equator in the central tropical Pacific compared to the observations, which may be largely due to strong upwelling along the equator. Meridional sections of climatological annual mean temperature (not shown), indeed, indicate a sharp rise in the isotherms at the equator in the MRI model. In the GFDL model, on the other hand, the MLD peaks at 100 m near the dateline which is 20~30 m greater than in the observations and the MRI model. Note also that the location of the maximum MLD is significantly shifted to the west in the GFDL model as compared to the observations and MRI model. These model biases may be associated with deficiencies in the mixed-layer physics used.

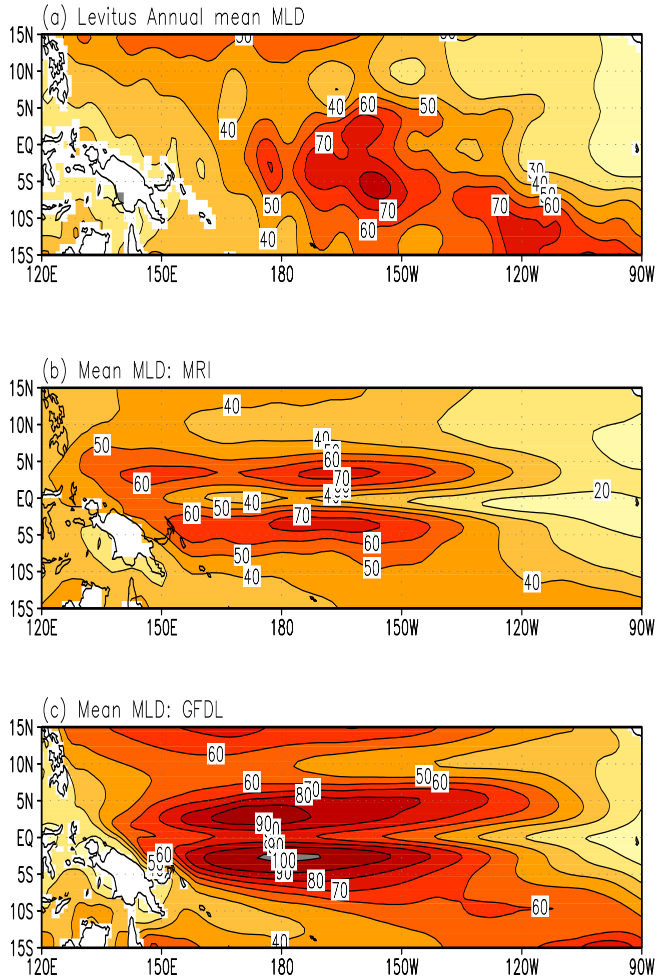

Fig. 3.4.B1 Climatological mean mixed layer depth (MLD) in the tropical Pacific based on the Levitus data (1982). Contour interval is 10 m and shading indicates values above 50 m. Climatological annual mean MLD simulated in the control experiment for (b) the MRI model and (c) the GFDL model. The analyzed period is the last 100 years for the control experiment.

MLD in the 2xCO2 Experiment

The mean MLD under the increased greenhouse gases scenario in the two CGCMs is presented in Figure 3.4.B2a and b. The panels can be compared to Figure 3.4.B1b and c (*i.e.*, the control experiments). There is similarity in the spatial pattern of the mean MLD between the two experiments for both CGCMs, namely a pair of deep MLDs which are at a maximum off the equator in the western and central equatorial Pacific, and a shallow MLD in the eastern tropical Pacific. In the tropical Pacific, the mean MLD ranges from 20 to 50m in the MRI model and from 20 to 80 m in the GFDL model. The greatest differences in mean MLD between the two experiments in the MRI and GFDL models are found in the central and western equatorial Pacific, respectively, consisting in a shallowing of 5 to 30 m. The maximum difference of mean MLD between the control and the 2xCO2 experiments (not shown) is observed in the region of the deepest simulated MLD in the control experiment in both models, that is, off the equator (*i.e.*, 2~3°N and 2~3°S) around the central equatorial Pacific (180°E–150°W) in the MRI model and in the western equatorial Pacific (150°–180°E) in the GFDL model. For more details we have also provided the ratio of mean MLD between the control experiment and the 2xCO2 experiment in the MRI (Fig. 3.4.B2c) and GFDL (Fig. 3.4.B2d) models. This ratio is less than 1 over most of the basin for both models (the exceptions are a region around the northeastern tropical Pacific for the MRI model, and in the south-central tropical Pacific for the GFDL model), indicative of shallowing of the MLD under global warming. Interestingly, the ratios of MLD changes are not homogeneous in the MRI model, unlike the GFDL model which exhibits a more uniform pattern. The MLD changes in the MRI model are projected to be large in the central equatorial Pacific with an off-equatorial maximum in both hemispheres (Fig. 3.4.B2c). In contrast, the MLD changes are small in the eastern equatorial Pacific, where the ratio values are around 0.8~0.9. On the other hand, the ratio values for MLD changes in the GFDL model are nearly uniform in the equatorial Pacific, where they are around 0.8~0.9 over most of the basin. These results indicate first, that changes in the MLD due to climate warming do not respond linearly in the equatorial Pacific (*cf*. the MRI model, which exhibits very distinct patterns of MLD in both experiments) and second, that there is great uncertainty about the MLD changes under climate change projections, considering the above-mentioned differences between both models.

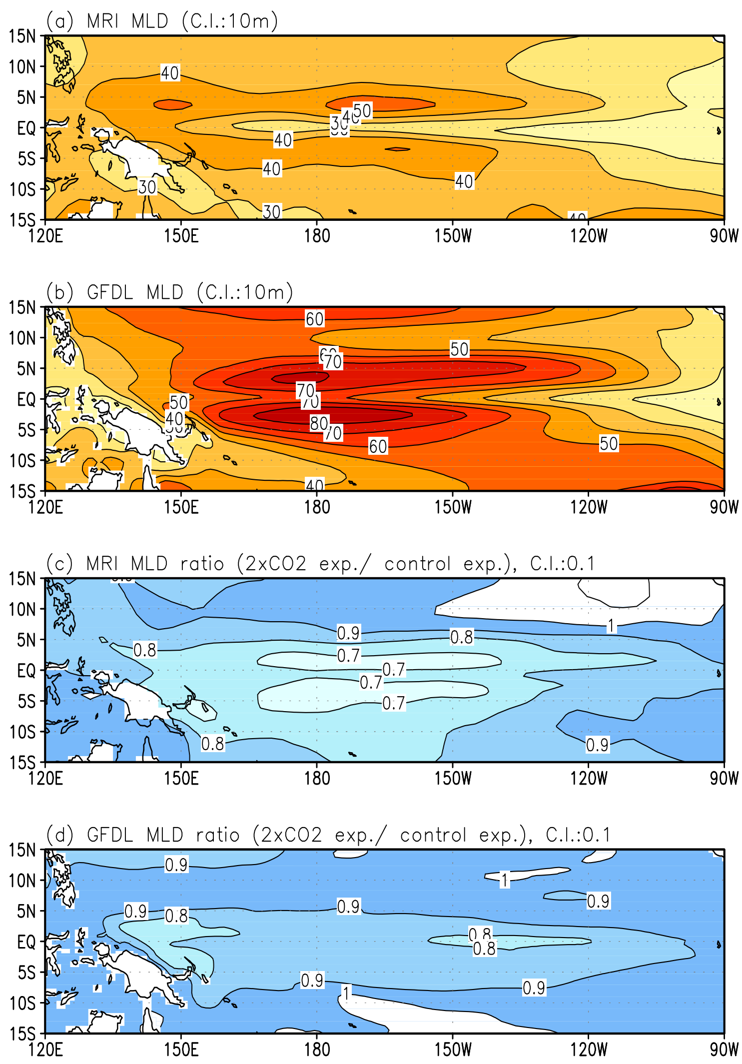

Fig. 3.4.B2 (a) and (b) are the same as in Fig. 3.4.B1b and c, except for the 2xCO2 experiment. Contour interval is 10 m. (c) and (d) show the ratios of MLD changes from the control experiment to the 2xCO2 experiment in the MRI model and the GFDL model, respectively. Contour interval is 0.1; shading indicates below 1.0.

Relationship between the MLD and Mean SST

The fact that the GFDL model simulates a deeper MLD than the MRI model in the control experiment (*i.e.*, Fig. 3.4.B1b and c) may influence the response of the tropical Pacific mean sea surface temperature (SST) to global warming in the two CGCMs. By definition, the mixed layer is the quasi-homogenous region of the upper ocean in terms of physical quantities like temperature and salinity. Therefore, a deep or shallow MLD may influence changes in mean SST through the homogenous distribution of heat flux forcing induced by global warming.

Changes in mean SST from the control experiment to the 2xCO2 experiment (*i.e.*, 2xCO2 minus the control) in the MRI and GFDL models are shown in Fig. 3.4.B3a and b, respectively. The two models exhibit El Niño-like warming trends under the doubled CO_2 concentrations and have quite different characteristics. Whereas in the MRI model the warming is projected to be considerable over a large portion of the central and eastern tropical Pacific, the warming in the GFDL model is centered along the equator in the central and far eastern Pacific. In addition, the tropical Pacific mean SST increases by about 2.6 to 3.6°C in the 2xCO2 experiment for the MRI model, which is almost double the increase in the GFDL model (*i.e.*, 1.6~1.8°C). This indicates that the climate sensitivity (the equilibrium mean temperature change following a doubling of the atmospheric CO_2 concentration) is different in the two CGCMs. Our results suggest that the deeper the mean MLD simulated in the control simulation, the less the warming rate of mean SST simulated in the 2xCO2 experiment (*cf.* Figs. 3.4.B2 and 3.4.B3). In order to examine the possibility that the heat flux differences between the two CGCMs can make a contribution to mean SST changes in the 2xCO2 experiment, we display the differences of the heat fluxes in the two CGCMs (*i.e.*, the MRI model minus the GFDL model) in the control experiment and the 2xCO2 experiment, respectively (Fig. 3.4.B4a and b). If the heat flux differences between the two CGCMs are comparable in the two experiments, one may conclude that the differences in MLD can be considered responsible for the different warming in the two CGCMs. Figure 3.4.B4a and b indicates that the net heat flux in the MRI model is smaller than that in the GFDL model in most regions of the equatorial Pacific for both the control experiment and the 2xCO2 experiment, which means that the ocean absorbs more heat flux from the atmosphere in the GFDL model than in the MRI model in both experiments. Furthermore, the net heat flux differences in the two CGCMs are comparable in the equatorial Pacific between the control experiment (Fig. 3.4.B4a) and the 2xCO2 experiment (Fig. 3.4.B4b), supporting the view that the heat flux differences between the two CGCMs make a small contribution to mean SST changes from the control experiment to the 2xCO2 experiment.

In a warmer climate, a shallowing of the MLD is expected in association with a more stratified ocean. Indeed, when the climate warms, the ocean's surface becomes warmer and the water column tends to stabilize. This suggests that different ratios of MLD shallowing under global warming in the MRI and GFDL models are related to different SST warming rates (Fig. 3.4.B3a and b). The shallowing of the MLD is greater in the MRI model than in the GFDL model, and this is associated with greater warming of mean SST in the MRI model than in the GFDL model. As we argue above, the deeper the mean MLD simulated in the control simulation, the less the warming rate of mean SST simulated in the 2xCO2 experiment. The reduced warming rate of mean SST then results in less shallowing of the MLD simulated in the 2xCO2 experiment. These results illustrate the feedback process of the MLD–SST changes from the control experiment to the 2xCO2 experiment. For instance, a shallow MLD in the control experiment is associated with relatively large SST warming through more global-warming-induced heat flux trapped around the near surface layer in the 2xCO2 experiment. This leads to a more stratified ocean. A large change in stability is associated with a significant MLD shallowing rate which, in turn, feeds back on the tendency of SST to increase under heat flux induced by global warming. Such processes are reversed for a deeper MLD in the control experiment. Figure 3.4.B5 displays a schematic of such a feedback process in the MLD–SST changes. We argue here that the MLD is a key parameter for regulating the response of tropical Pacific mean SST due to increasing greenhouse gases in a CGCM. On the other hand, equatorial wave dynamics also enables us to understand the variation of the tropical Pacific on interannual and longer times scales as well as the mean state. Therefore, in the next subsection we examine the impact of climate change associated with MLD variability on some aspects of oceanic dynamical processes.

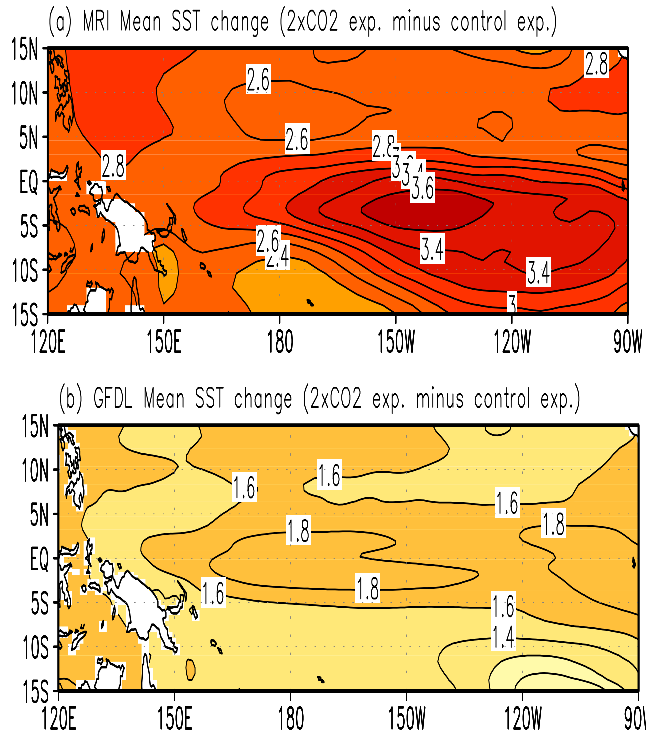

Fig. 3.4.B3 Difference in annual mean SST simulated in (a) the MRI model and (b) the GFDL model between the control experiment and the 2×CO2 experiment. Contour interval is 0.2°C.

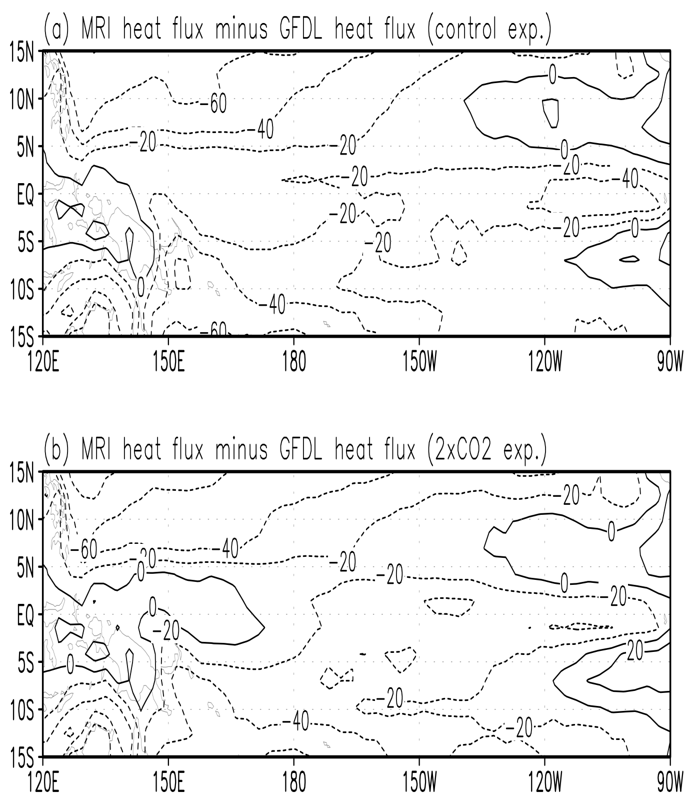

Fig. 3.4.B4 The differences of the net heat fluxes in the two CGCMs (*i.e.*, the MRI model minus the GFDL model) in (a) the control experiment and (b) the 2xCO2 experiment. Contour interval is 20 W m^{-2} and dashed line denotes below zero.

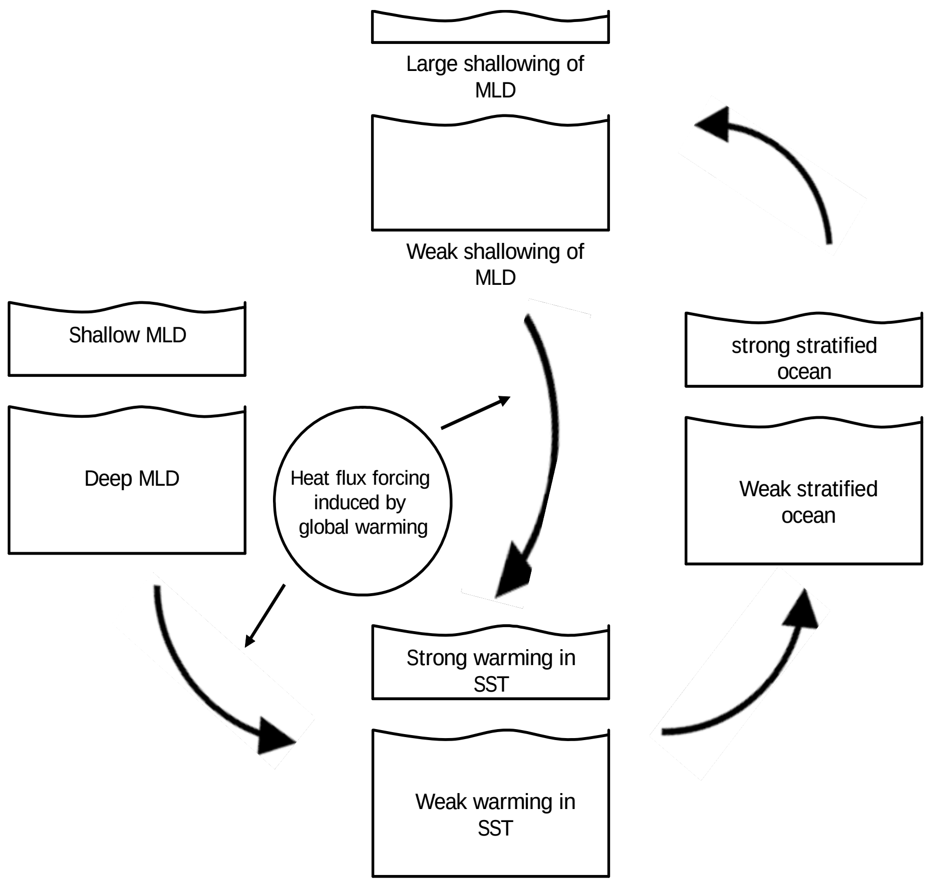

Fig. 3.4.B5 Schematic diagram showing the feedback process of the MLD–SST changes under global warming.

Relationship between the MLD and ENSO

According to previous studies, the predominant pattern of MLD variability in the tropical Pacific is coherent with ENSO (Carton *et al*., 2008). To examine MLD variability associated with ENSO in the two experiments, we begin by showing the standard deviation of total sea surface temperature anomaly (SSTA) simulated in the control experiment (Fig. 3.4.B6) in the two CGCMs. The anomaly is defined as the deviation from the mean annual cycle calculated over the analyzed period without removing any trends. For comparison, we show the same results based on the monthly mean observed SST data from the National Climate Data Center (Smith and Reynolds, 2004) for the period of 1901–2005 (Fig. 3.4.B6a). The SSTA standard deviation for the MRI model (Fig. 3.4.B6b) and the GFDL model (Fig. 3.4.B6c) has a maximum center in the central and eastern tropical Pacific, respectively, which differs somewhat in terms of spatial structure and amplitude compared to observations. Both models simulate SSTA variability that extends too far into the western Pacific compared to observations. The composite of El Niño during the boreal winter (not shown), which is defined when the NINO3.4 SST index during winter is above its one standard deviation, also shows that the maximum SST center of the simulated El Niño from both models extends to the west compared to the observations. Note that the NINO3.4 SST index is defined as the time series of the SSTA averaged over the region 5°N–5°S, 170°E–240°E. The standard deviation of the NINO3.4 SST index is 0.66°C for the MRI model, 0.98°C for the GFDL model and 0.74°C for the observations. A power spectral analysis of the simulated NINO3.4 SST index (not shown) indicates a spectral peak around 24 months in the MRI model for the control run, which is shorter than that in the GFDL model (*i.e.*, 37 months; see also van Oldenborgh *et al.* (2005).

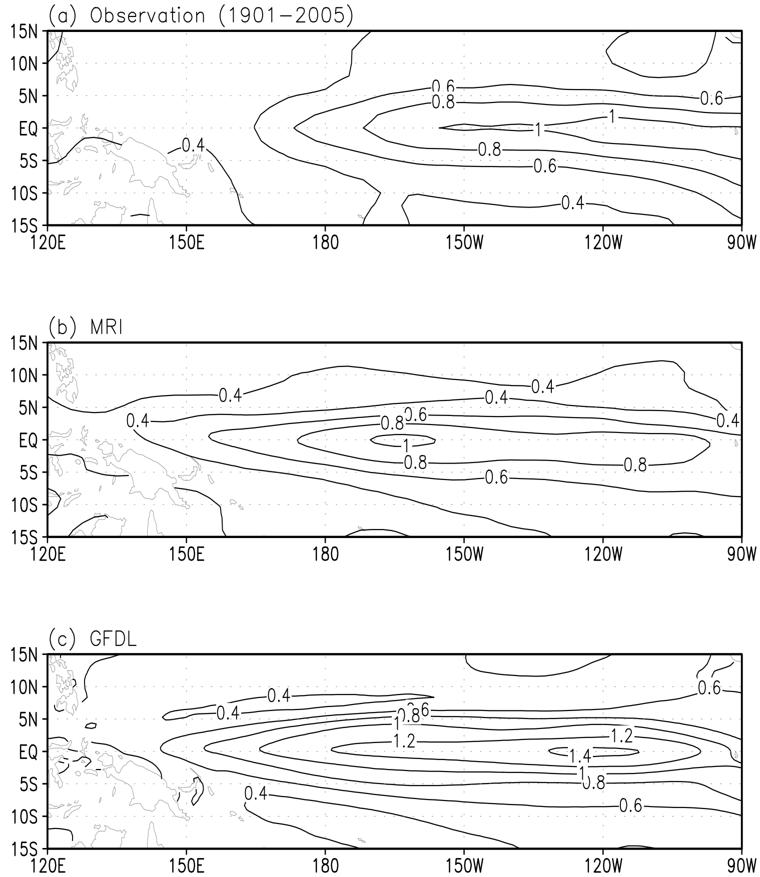

Fig. 3.4.B6 (a) is the standard deviation of SSTA variability for the observations for the period of 1901–2005. (b) and (c) are the same as in (a) except for the control experiment for (b) the MRI model and (c) the GFDL model. Contour interval is 0.2°C.

In order to isolate the variability of the MLD associated with ENSO, the simultaneous linear regression coefficients between the MLD anomaly and the NINO3.4 SST index were estimated for both models (Fig. 3.4.B7a and b). The MLD anomaly is defined by the deviation from the climatological annual cycle over the entire analyzed period. The most obvious pattern of MLD anomalies in the equatorial Pacific, associated with ENSO, is a zonal see-saw to the east and west of 150°~160°W in both CGCMs. During a warm event, the MLD is shallow (deep) in the central-western (eastern) tropical Pacific. The spatial patterns of Fig. 3.4.B7a and b resemble the structure of the mean MLD (see Fig. 3.4.B2) although in the GFDL model they are less symmetrical towards the equator. These structures are closely related to anomalous zonal wind stress associated with ENSO (Fig. 3.4.B7c and d). During a warm event, anomalous eastward zonal wind stress forces equatorial downwelling Kelvin waves and upwelling Rossby waves. The latter is associated with the shallower MLD off the equator. Since anomalous wind stress is not centered on the equator (*i.e.,* is slightly to the south), cyclonic wind stress curl off the equator is expected to effectively amplify the upwelling in the southern hemisphere more than in the northern hemisphere. This results in a larger amplitude of regressed MLD on ENSO variability in the southern hemisphere in both CGCMs compared to the northern hemisphere (Fig. 3.4.B7a and b). Furthermore, the maximum center of regressed zonal wind stress is displaced to the west in the GFDL model (Fig. 3.4.B7d) compared to the MRI model (Fig. 3.4.B7c). This causes the maximum amplitude of regressed MLD to shift to the west in the GFDL model compared to the MRI model.

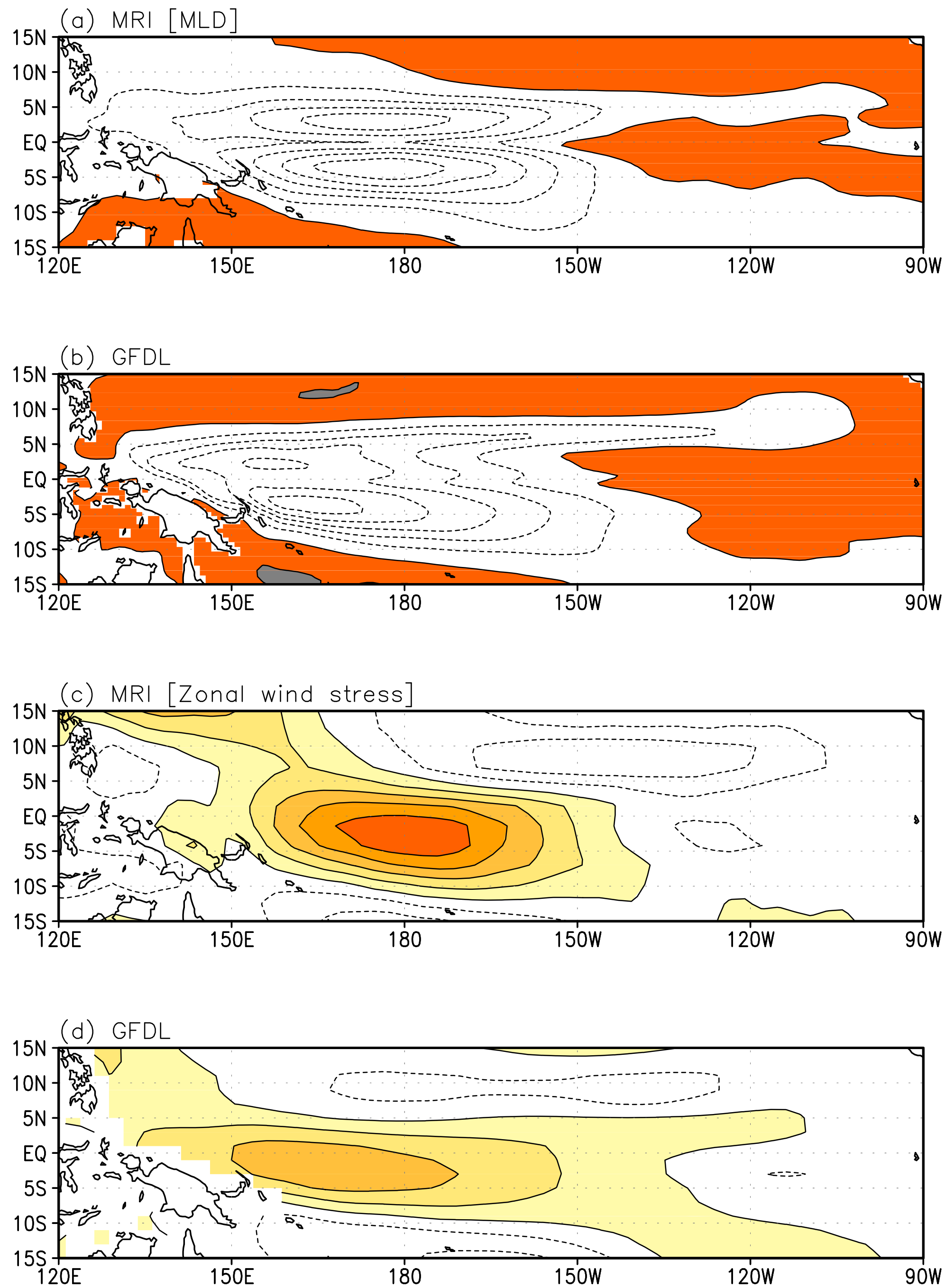

Fig. 3.4.B7 Simultaneous linear regression coefficients between the MLD anomaly and the NINO3.4 SST index in the control experiment for (a) the MRI model and(b) the GFDL model. (c) and (d) are the same as in (a) and (b) except for the anomalous zonal wind stress. Contour interval in (a) and (b) is 5 m/°C and 0.005N/°C*m^2 in (c) and (d). Shading indicates positive.

To further investigate the relationship between the MLD and ENSO, we present a scatter diagram comparing the MLD anomalies averaged over 5°N–5°S, 150°W–150°E (hereafter referred to as the MLD index) and the NINO3.4 SST index in the control experiment for the MRI model and the GFDL model, respectively (Fig. 3.4.B8a and b). The averaged region for the MLD index is based on the above maps of simultaneous linear regression coefficients (Fig. 3.4.B7a and b). As can be seen in Fig. 3.4.B8a and b, there is a clear negative relationship between the MLD index and the NINO3.4 SST index in both CGCMs. The simultaneous correlation between the two indices is –0.88 and –0.77 in the MRI model and the GFDL model, respectively, which exceeds the 95% confidence level. Simply put, Figure 3.4.B8 indicates that the stronger El Niño (La Niña), the shallower (deeper) the MLD in the western and central tropical Pacific. It is worth noting that an asymmetry of the relationship between the MLD index and the NINO3.4 SST index appears in the GFDL model compared to the MRI model. The correlation coefficient between the positive (negative) NINO3.4 SST index and the MLD index is –0.82 (–0.27) in the GFDL model, whereas the correlation coefficient between the positive (negative) NINO3.4 SST index and the MLD index is –0.77 (–0.67) in the MRI model, respectively. The low correlation during La Niña in the GFDL model may reflect that the MLD in the western tropical Pacific is already deep in the GFDL model, as shown in Figure 3.4.B1c, and its increase during La Niña shows much larger scattering. We further speculate that such a difference is associated with the difference in the mean state of the tropical Pacific between the two CGCMs (namely, the climatological mean SST is warmer in the western and central equatorial Pacific in the GFDL model than in the MRI model (not shown)). Therefore, anomalous surface temperature, which is closely associated with the variation of MLD, may be different when the same magnitude of El Niño or La Niña occurs in the MRI model and the GFDL model.

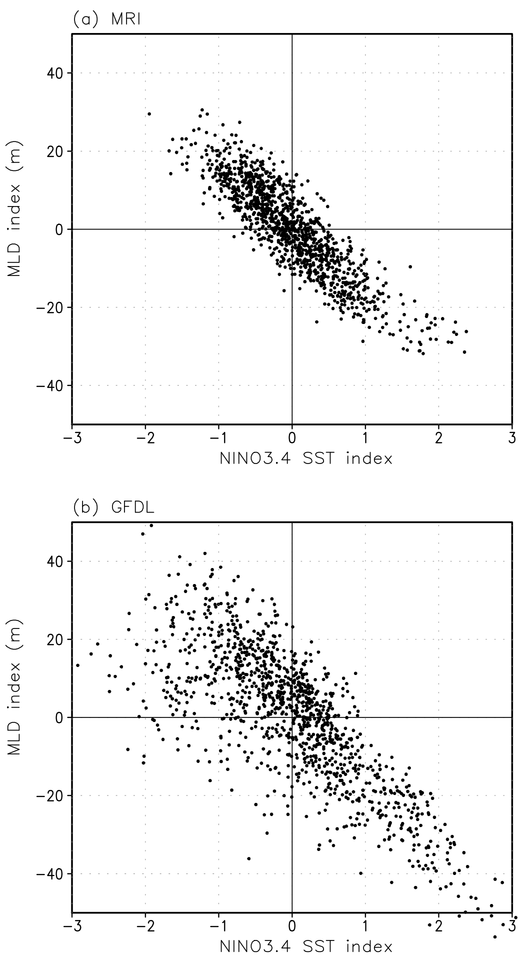

Fig. 3.4.B8 Scatter diagram comparing the MLD index and the NINO3.4 SST index in the control experiment for (a) the MRI model and (b) GFDL model. The *x*-axis indicates the NINO3.4 SST index and the *y*-axis indicates the MLD index. Units are °C for the *x*-axis and meters for the *y*-axis.

Changes in ENSO amplitude under an increase in CO_2 concentrations are quite different in the MRI model and the GFDL model. The SSTA standard deviation is markedly increased in the 2xCO2 experiment for the MRI model. The standard deviation of the NINO3.4 SST index is 1.11°C in the 2xCO2 experiment, which is significantly larger than that in the control experiment (*i.e.*, 0.66°C). In contrast, in the GFDL model ENSO amplitude is slightly reduced from the control experiment to the 2xCO2 experiment. The standard deviation of the NINO3.4 SST index is 0.98°C (0.88°C) in the control (2xCO2) experiment in the GFDL model. In order to show changes in the relationship between MLD and ENSO under global warming, we applied the same analysis as the one used to derive Figure 3.4.B8 in the 2xCO2 experiment. Results are presented in Figure 3.4.B9. Similar to the control experiment, the MLD index is highly negatively correlated with the NINO3.4 SST index in the 2xCO2 experiment for the MRI model (simultaneous correlation coefficient, –0.89). However, one may find there are subtle differences between Figures 3.4.B8 and 3.4.B9 when the amplitude of the NINO3.4 SST index is large. For instance, the MLD does not deepen as much as in the 2xCO2 experiment compared to the control experiment when the NINO3.4 SST index reaches large values. Note also that a simultaneous correlation coefficient between the two indices is –0.31 when

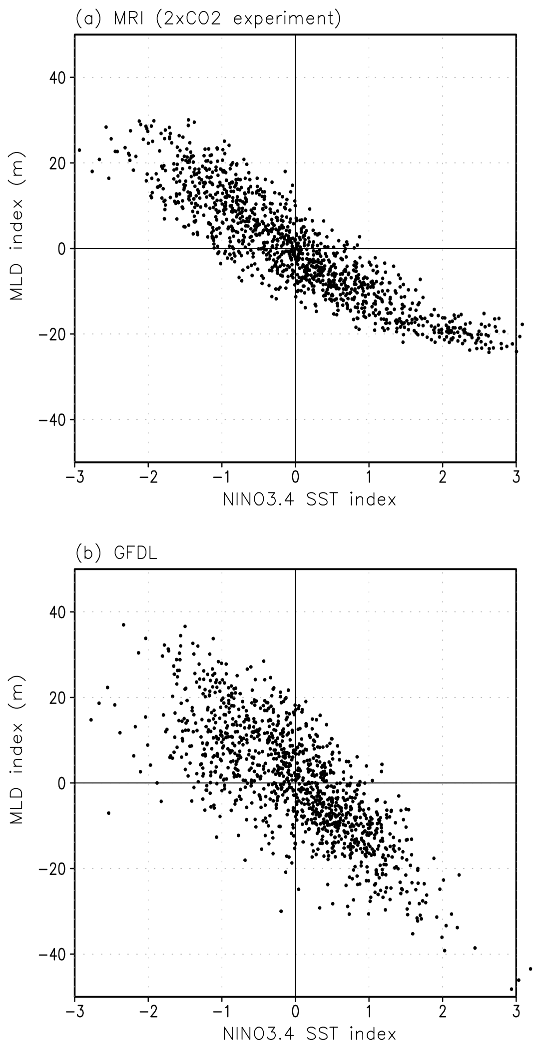

Fig. 3.4.B9 (a) and (b) are the same as in Fig. 3.4.B8a and b, except for the 2xCO2 experiment.

the NINO3.4 SST index is above 2.0°C in the 2xCO2 experiment. Simply put, this result suggests that the non-linearity between the MLD and ENSO is enhanced from the control experiment to the 2xCO2 experiment in the MRI model. On the other hand, in the GFDL model there is little change in the relationship between the two indices from the control experiment (Fig. 3.4.B8b) to the 2xCO2 experiment (Fig. 3.4.B9b). The simultaneous correlation coefficient between the two indices is –0.77 in the control experiment and –0.76 in the 2xCO2 experiment. In addition, a linear relationship between the MLD index and the NINO3.4 SST index can still be distinguished for large amplitude of El Niño. Note that a simultaneous correlation coefficient between the two indices is –0.75 (–0.69) when the NINO3.4 SST index is above 2.0°C in the 2xCO2 experiment (control experiment). This result indicates that the linear relationship between the MLD index and ENSO is unchanged despite an increase in CO_2 concentrations.

Acknowledgements S.-W. Yeh was supported by the National Research Foundation of Korea Grant funded by the Korean Government (MEST), (NRF-2009-C1AAA001-2009-0093042).

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3.5 Interactions between global climate and World Ocean ecosystems

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Abstract

The role of the World Ocean in global climate change is analyzed from two points of view: (1) heat energy accumulation and distribution in the ocean and its discharge into the atmosphere as purely physical processes; (2) participation of living matter in the ocean in these processes. It is shown that living matter, especially phytoplankton, having the ability to absorb solar energy, change water transparency and react not only to the flow of heat energy, but also to extra weak fluctuations of electromagnetic and magnetic fields generated by external and internal sources, can be considered as an active forcing of climate fluctuations observed on different scales. Several mechanisms of climate–ecosystem interactions are identified.

Introduction

Climate change (CC) and its consequences are among the critical problems for modern day civilization. Due to the complexity of the problem, investigations are carried out in many directions and by many national and international organizations. A very important part of the problem – the impact of CC on the World Ocean ecosystems – was the main objective of the PICES/GLOBEC Climate Change and Carrying Capacity(CCCC) program. Significant results were obtained in modeling the processes of medium-scale living matter interactions and in observational data analysis. However, practically all investigations were directed from a climate to ecosystem (CC forced effects) perspective and took into account only the effects of energy and mass transport in the systems. The main objectives here are to (1) show the active role and significance of living matter in climate–ecosystem interactions, including informational flows; (2) analyze the main factors and possible mechanisms of their quick interaction and slow co-evolution; (3) outline directions of studies that should be promoted in the near future.

General Considerations

First, it is necessary to specify the notions of global climate (GC) and global climate change (GCC). We can define GC as the spatial–temporal distribution over the Globe of an ensemble of hydro-meteorological parameters (such as temperature, air pressure, winds, cloudiness, humidity, rainfall, seasonal variations) averaged over some conditional spatial and temporal scales L_a and T_a. Some uncertainty is inevitable in the notion. "Distribution" should be used in a stochastic sense as probability distribution that can be described by moments of all orders (*e.g.*, mean, dispersions, correlations, spectra, asymmetry). The same is true for each parameter. Averaging scales L_a and T_a generally imply: (1) in space – regions with insignificant dispersions of climate parameters (depending on requirements, which are very different for land and ocean); (2) in time, 5–10 years, taking into account averaged intra-annual (seasonal) variations as a very important parameter.

The climatic parameters are defined by processes in the climatic system which includes ocean, atmosphere, land, the Earth's biota, and which has become more evident in the last decades, human civilization as a particular sub-system. Changes on scales greater than L_a and T_a are going on continually, and the parameter distributions cannot repeat because the state of the system is subject to continual changes. However, quasi-periodicities are possible when, neglecting insignificant changes, it is possible to look at close states as repeated and in limited spans of time to deal with climate variations.

Our hypothesis is that changes in climate energy balance during all times were limited, and a change can be looked at as a part of some longer fluctuation. Fluctuations in all climatic parameters have very wide spectra, and to define CC for specified periods of time we should find reference levels, that is, some more or less long periods of small changes, at least in mean values and dispersions (understanding “small” as not essential for our activity), to find quasi-stationary states. What are these states and what should be the difference between sets of climatic parameters to discriminate between states? As for transitions between states – how slow or quick should they be for us to interpret them as *evolution* or as a *regime shift*?

There are no exact answers to these questions due to the random character of the multi-parameter processes involved and their dependence on the particular problems that should be resolved. The situation becomes much simpler when we deal with globally averaged temperature because its changes represent changes in heat energy content in the system and, to some extent, its possible transformations into mechanical energy of the Earth’s atmosphere and ocean currents. Long-term cycles of global temperature resulting from changes in solar insolation can be due to variations in the tilt of the Earth’s rotation axis, procession of the equinoxes along the Earth’s elliptic orbit, and changes in the eccentricity of the orbit. The relevant periods are from about 100,000 to thousands of years (Lindzen, 1994). Much shorter periods on the spectrum can be attributed to higher harmonics of the 24,000- and 19,000-year cycles, related to long-term cycles in ocean–atmosphere interaction. Orbital motions lead to not only small variations in averaged insolation, but also to considerable changes in its geographical distribution. No less important are variations and inversions of the Earth’s magnetic field (Valet and Courtillot, 1992). Their effects on climate can be realized by (1) their influence on the upper atmosphere and magnetosphere electromagnetic fields and consequent changes in the upper baric and velocity fields, and (2) their influence on ocean water optical properties directly and *via* living matter.

On the scale from decades to thousands of years, the most pronounced climate-related effects can be attributed to solar activity. These effects can be realized through many different mechanisms, which can be in phase, out of phase or in opposite phases. Among the processes being examined by many investigators are changes in total solar irradiance (solar constant) leading to fluctuations in the amount of heat energy reaching the Earth’s surface. In solar cycles, that is, on decadal scales, the solar constant fluctuations during the last millennium were of order 0.1%, and no related substantial trends in global temperature were observed. Temperature is directly related to energy, but we should understand that (1) its globally averaged value is not very useful for CC description if it does not exceed some unknown critical values; (2) a large part of heat energy is converted into kinetic energy of the ocean and atmosphere movements and cannot participate in the description of CC while the interchange between heat and kinetic energy is going on in a wide spectrum of time and space scales; (3) energy comes to the Earth unevenly, and the main energy of climate fluctuations is not in mean values, but in dispersions of thermal and dynamic fluctuations, the mean values being only residuals of these fluctuations. Nevertheless, as a result of many studies, it was stated in the Intergovenmental Panel on Climate Change Fourth Assessment Report (IPCC AR4; IPCC 2007) that considerable climate change has been going on quickly during the last decades. So the main question is: Where is the energy coming from? What are the main factors affecting the global energy balance?

If we look at the Earth’s biosphere, it is evident that its changes must be related to climate variations, but land ecosystems are under the extremely strong influence of anthropogenic factors, and separating out the effects of climate becomes rather difficult. The ocean ecosystems change on larger time scales, and are directly influenced by the natural environment so that it is easier to follow their dependence on local climate conditions. Here, interesting facts arise. Fluctuations of species and population abundance are an inherent property, but in many cases synchronous fluctuations of abundance of different species in different parts of the ocean are observed, though local climate conditions are going on in opposite directions (West and East parts of the North Pacific as an example). Other striking observations are that changes in ecosystem characteristics cannot only be synchronous with climate change, or follow them with different lags, but can also forestall them. An example of such possibilities is shown in Figure 3.5.1. Lags of about 2–3 years in both directions can be seen. To explain such situations, we should look for global factors that are not only inside the climate–biota system, but can independently influence climate and biota.

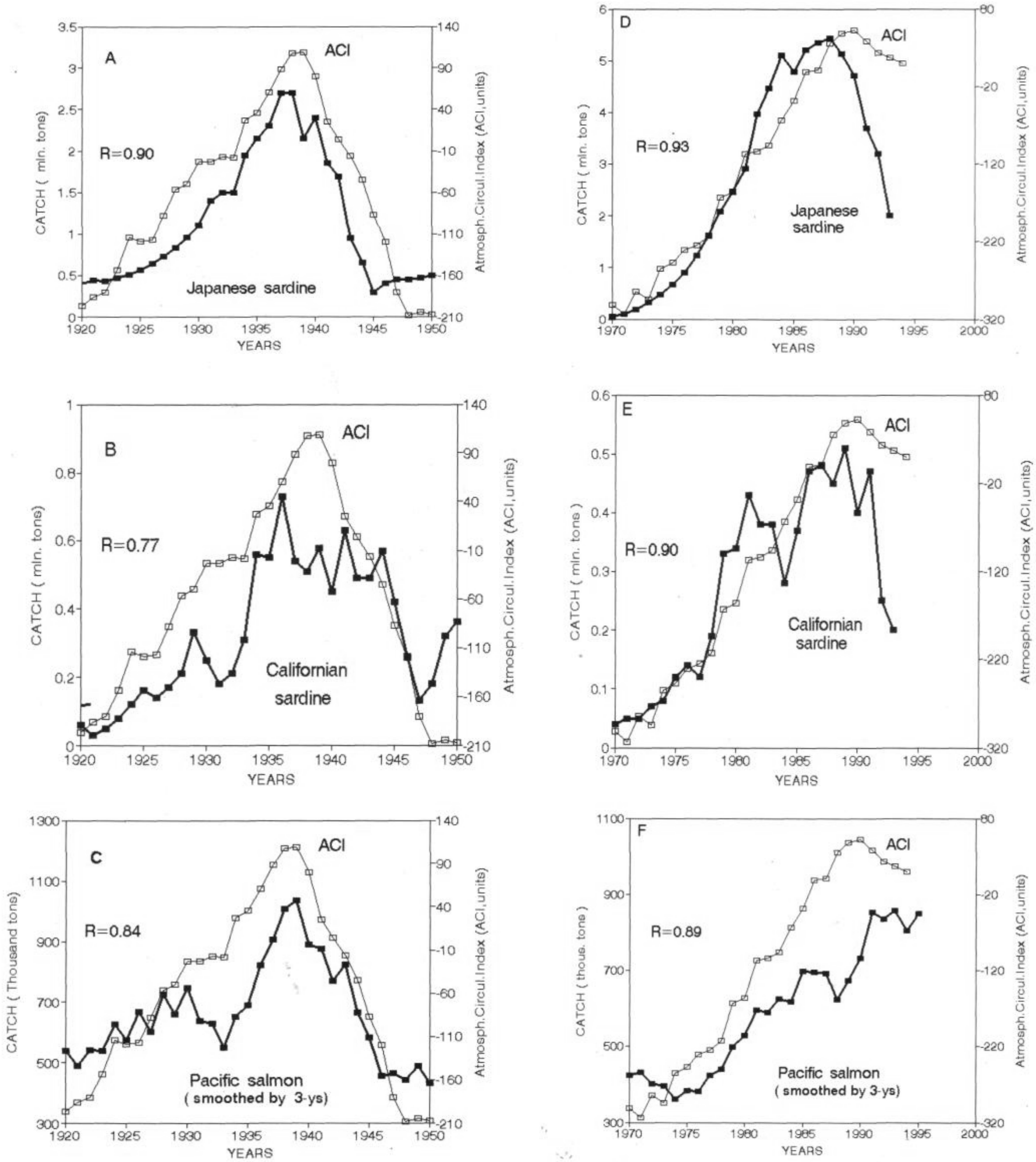

Fig. 3.5.1 Relationship between salmon and sardine catch and the Atmospheric Circulation Index (ACI) trend in the North Pacific for the periods 1920–1950 (A, B, C) and 1970–1993 (D, E, F) (from Klyashtorin, 1997).

Climate Change and the World Ocean – Energy Considerations

If we limit ourselves to the analysis of temperature as the main climatic parameter, there can be two processes leading to CC: (1) change of space–time distribution of temperature over the Globe without change in dispersion, that is, of full energy of fluctuations; (2) change in dispersions that means change in energy space–time distribution. Evidently, we now have the second case.

The energy sources can be internal and external to the Earth. The only important external energy factor is solar radiation, and it has not changed considerably during the last decades. To explain observed trends of global temperature, the main attention in most studies has been given to greenhouse gases, which are not sources of energy but can be treated as internal factors, changing the balance between incoming and outgoing radiation. We do not discuss here all findings about the relevant processes, but draw attention to the other aspect of the problem. If we assume that total solar radiation does not change substantially (at least, it cannot fully explain the observed trends in global temperature), and effects of solar activity on the atmosphere do not produce long trends in climate (these effects are fluctuating with short periods and are graded down by averaging), we should look for the answer in the Earth's surface properties to assimilate, accumulate, and discharge solar energy into the atmosphere.

There are only two systems on the Earth effectively accumulating solar energy for the long run: (1) plants on land and in the ocean and (2) the ocean itself. Terrestrial ecosystems can produce biomass comparable to that in the ocean, but there is no accumulating system that could, in the long run, discharge and convert the immense amount of this energy into mechanical energy of the atmosphere and ocean. Assimilation of solar energy on land has changed drastically during the last centuries. Deforestation and urbanization on all the continents have led to large parts of land, instead of assimilating and converting solar energy into organic green matter (coal deposits are due to such processes), are transformed into large areas, extremely heated in daytime and emitting extreme energy at night. This leads to a rise in local energy gradients in space and time (particularly land–ocean heat content differences) but at present, retention of heat on land is not considerable.

In the ocean, which occupies 72% of the Earth's surface, processes of effective assimilation and accumulation of solar energy in plants (phytoplankton), and in the water itself, are effectively going on, and they generally tend to go in opposite directions: the more solar energy is assimilated by phytoplankton (PP), the less energy is accumulated in water layers. Light is absorbed with the help of chlorophyll pigments in photosynthesis and scattered by plants so that it can penetrate to a depth of about 150 m in clear water with low concentrations of PP (the lower limit of the photic layer in oligotrophic waters) and only to 15–20 m in mid-latitude waters with high concentrations of PP. In both cases, the depth of solar energy penetration is not limited by only optical properties of water. Due to multi-scale vertical and horizontal mixing and deep ocean circulation, it can be accumulated at all depths and in all parts of the ocean, but in general, the interrelationship between PP and photic layer depth is realized. Part of the solar energy absorbed by plants is scattered back into the atmosphere, and high concentrations of PP in a thin layer will augment back radiation and influence the total energy balance.

Several quantitative estimates, compiled in Lappo *et al*. (1990), can illustrate the comparative significance of thermal processes in the ocean. Total solar energy input to the ocean is $E_{inc} = 9 \times 10^{23}$ J/yr, evaporation energy is $E_{eva} = 8 \times 10^{23}$ J/yr, heat advection energy is $E_{adv} = 10^{23}$ J/yr, energy of atmospheric movements is $E_{atm} = 10^{21}$ J/yr, photosynthetic energy in the ocean is $E_{ph} = 10^{20}$ J/yr (up-to-date estimates give a value of 10^{21} J/yr), fuel combustion energy is $E_{comb} = 5 \times 10^{19}$ J/yr (at present, at least twice as much), consumption of energy by mankind $E_{cons} = 5 \times 10^{20}$ J/yr (at present, also twice as much).

These estimates may be supplemented by the results from the IPCC AR4 Synthesis Report, Working Group 1, Chapter 5 (IPCC, 2007). The ocean heat content change for the period from 1961–2003 was 14.2×10^{22} J from a total of 15.9×10^{22} J. It was about 30 times more than in the atmosphere and about 20 times more than on the continent. If we take into account that the heat to continents is transported by atmosphere currents from the ocean, the decisive role of the ocean in climate formation becomes obvious. The highest rate of ocean heating was in the periods 1965–1980 and 1985–2005, and the main contribution in heat content gives the upper layer 0–700 m. The largest warming occurred in the sub-antarctic region, which is known to have maximum plankton concentration.

Two important facts should be emphasized in these estimates: (1) Energies of fuel combustion, consumption and photosynthesis are close, and we know that photosynthesis supplies oxygen, which is consumed by fuel combustion. The oxygen balance shift for the benefit of combustion is very undesirable. On the other hand, if the part of the energy for photosynthesis increases, the part for atmosphere dynamics becomes smaller. (2) We see that energy of thermal processes is an order higher than energy of dynamic processes in the ocean and two orders higher than energy of atmosphere circulation. This means that even relatively small changes in ocean thermal energy will lead to considerable changes in the atmospheric state, which defines for us the most visible and important properties of climate.

The explanation of global warming by greenhouse effects, caused mainly by elevated CO_2 concentrations, implies that additional heat is supplied to the ocean by backscatter from the atmosphere, but having the estimated ocean/atmosphere ratio of energy content changes 30/1, we believe that greenhouse gases, even taking into account the rising greenhouse role of water vapor in the warmed ocean, are insufficient to explain the reported warming. It becomes evident that the main source of energy for CC is the World Ocean as the main energy accumulating system. To obtain a more exact view of the CC extent and its space–time properties, we need information about two processes: (1) mechanisms of changes in the ocean's accumulating properties and (2) accumulated energy discharge that includes energy redistribution in the ocean and its contribution to ocean–atmosphere interaction.

Climate Change, Sun and Life in the Ocean

Solar radiation is the main source of energy on the Earth and the relationship of CC with solar activity has been investigated for more than two centuries. However, "despite the increasing evidence of its importance, solar-climate variability is likely to remain controversial until a physical mechanism is established" (Kirkby, 2008). It is natural to obtain controversial results because (1) there is no single mechanism, but many different mechanisms, corresponding to different kinds of solar emanation – magnetic, electromagnetic, corpuscular, *etc*.; (2) in most studies, relationships were looked for in the form of statistical correlations which can well describe linear interrelations, but do not give reliable results for nonlinear processes which prevail in sun–climate interactions. The well studied pathway for solar and cosmic ray effects is through changes in atmosphere properties (ion-aerosol-cloud processes) with consequent changes in solar energy reaching the Earth's surface (non-uniform over the Globe) and direct influence on motions in the upper atmosphere. The climatic significance of these processes was analyzed by Kirkby (2008). Based on the estimates given in the previous section, we believe that changes in the assimilating capacity of the ocean as the main accumulator of solar energy are not less, and in long run, more important than changes in the atmosphere properties. The question is – What are the main factors affecting the energy absorbing capacities of the ocean? To answer this question we have to look more attentively into sun–climate–life interrelations.

We saw that primary production by PP takes up a considerable part of solar energy (from 10 to 70%) penetrating the ocean waters. At the same time, the depth of solar energy penetration depends on the optical properties of water, and these properties are determined by PP concentration. If there is some factor affecting PP concentration, it will inevitably change (1) the amount of solar radiation in the layer (the deeper the layer, the more radiation); (2) the amount of solar energy consumed by PP for new production. Because the influence of solar radiation on living matter has been studied for a long time and is not in doubt, we believe that it is the main factor affecting PP communities in the ocean. Though PP is sensitive to water temperature, the globally averaged change in temperature is too small to globally influence PP biomass. We believe that water and PP properties can change and have considerable anomalies not only due to internal processes, but also due to considerable changes in solar activity, which is generally related with sun spots represented by Wolf numbers (Wn). Figure 3.5.2 shows fluctuations of Wn monthly values from 1750– 2010. The spectrum of solar activity, if described by the spectrum of Wn, is very large – from several days (3–4, 7, 14, 27 days; 3, 4 months) through quasi-biennial to 11 and 22 years and further to 29, 38 and 85–87 years (Figs. 3.5.3 and 3.5.4). Figure 3.5.5 shows the statistical (averaged) spectrum of Wn for the period 1750–2010. The short-period part from 1 year to 2 months is especially highlighted in the insert to show very sharp peaks at 3, 4, and 5 months. Key scales of PP blooming and zooplankton feeding are measured in weeks, and the short anomalies in any forcing factors (see also the 27-day peak in Figure 3.5.4) have a greater probability to fall in resonance with natural biological periods, and so lead to considerable interaction between physical and biological processes.

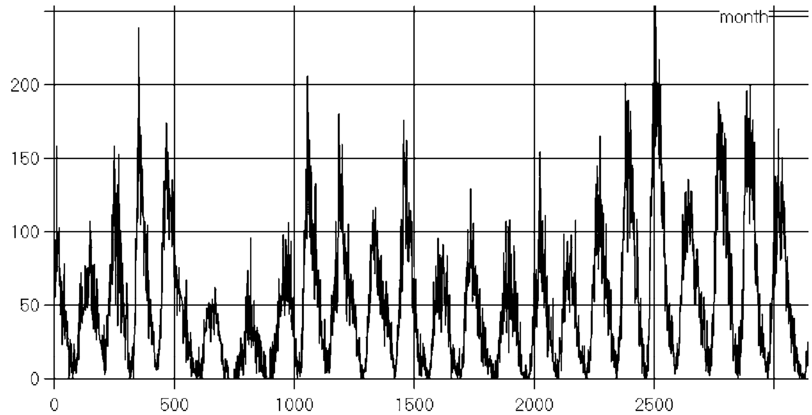

Fig. 3.5.2 Monthly values of Wn from 1750–2010.

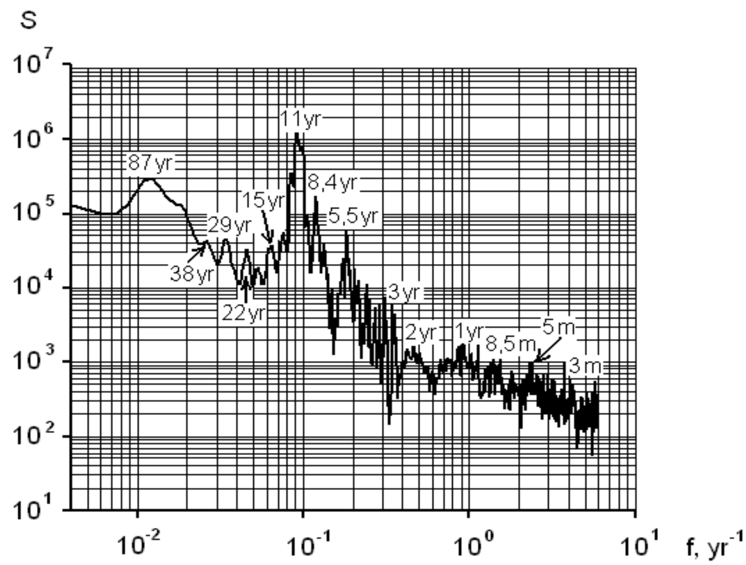

Fig. 3.5.3 Spectrum of monthly values of Wn for the period 1750–2010.

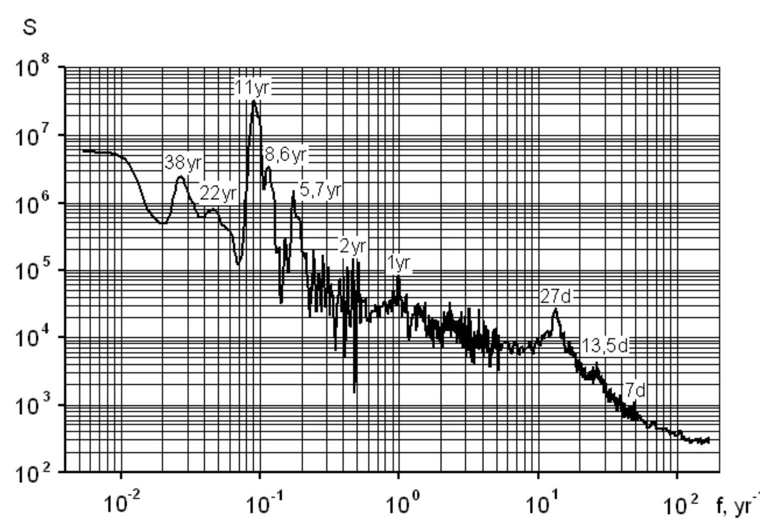

Fig. 3.5.4 Spectrum of daily values of Wn for the period 1818–2006.

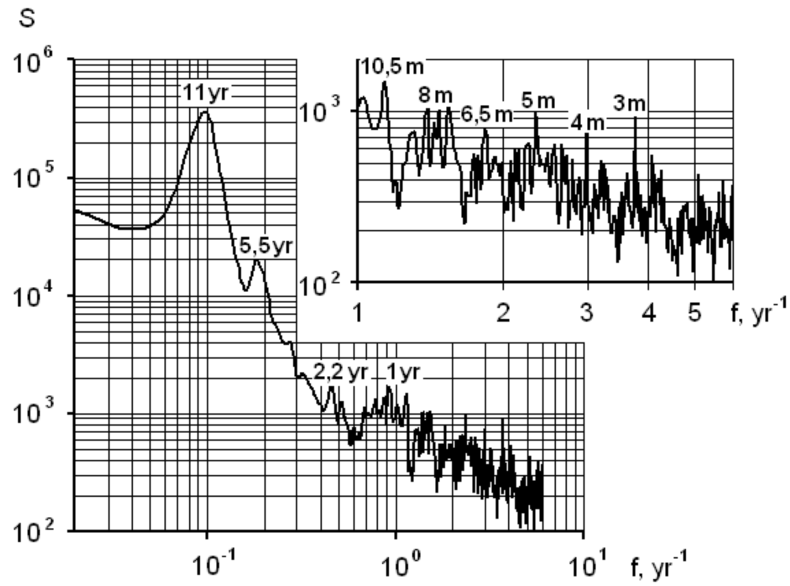

Fig. 3.5.5 Statistical spectrum of Wn fluctuations in the period from 1750–2010 obtained by averaging 22 spectra calculated over 50-year periods, taken with 10-year steps.

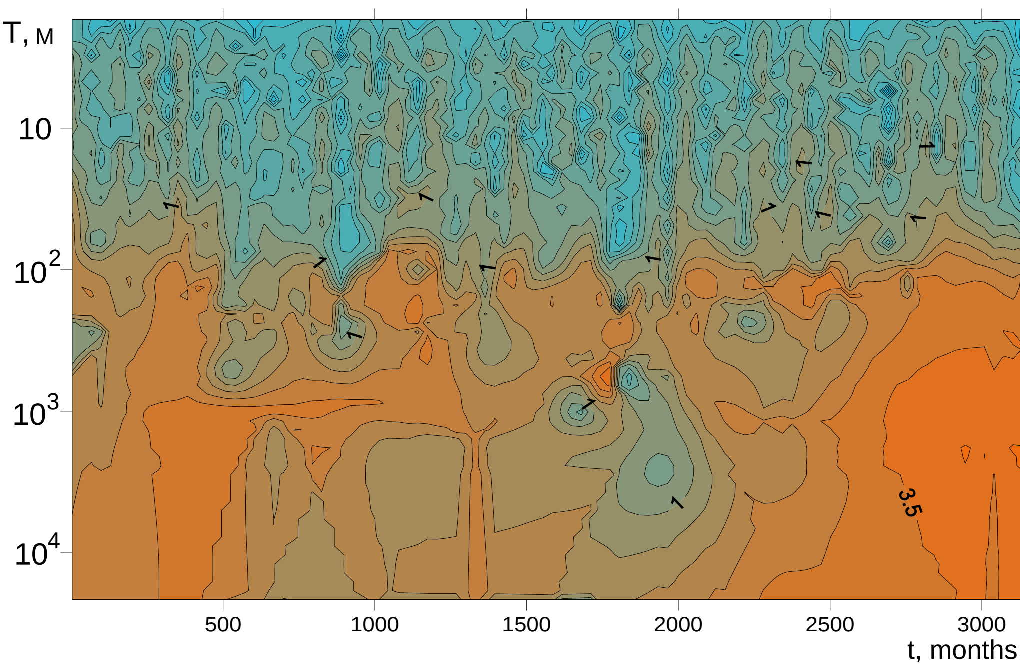

Fig. 3.5.6 Hilbert-Huang (H-H) spectrum of Wn for the period 1750–2010. Periods on the ordinate axis are in months.

In Figure 3.5.2 we can see that the amplitudes and frequencies of Wn are modulated, and the change of spectral structure with time may be important. The Hilbert-Huang (HH) spectrum (Huang *et al.*, 1998), describing the time–frequency–energy (or time–period–energy) distribution of Wn, is shown in Figure 3.5.6. The strip of maxima, corresponding to the 11-year cycle, is not uniform – there are times of high and low energy of Wn fluctuations, that is, there are considerable changes in solar activity on time scales of several decades (29, 38 and 87 years on our spectra are examples). On the other hand, it becomes obvious from the HH spectrum that short-period maxima are not self-contained, but grow out of the 11-year cycle to the shortest 2- to 3-month peaks.

The main cycles, thoroughly examined by many investigators, are 11 and 22 years. The largest amplitudes of energy response to the sun-induced fluctuations are in tropical regions of the oceans and in mid-latitudes and sub-polar regions (Tourre and White, 1995). In the tropics there is a maximum of available solar irradiance and a minimum of albedo. In mid-latitudes and sub-polar regions there are maxima of ocean–atmosphere interactions (especially in the western parts of the oceans) and high plankton concentrations. So we can anticipate that the onset of heat content anomalies in mid-latitudes is due mainly to changes in PP concentration, and in tropical regions to wind and currents fluctuations. The low velocity of equatorial currents will lead to higher heat accumulation and *vice versa*. If heat content anomalies in large areas arise, two mechanisms are switched on to spread them over the Globe: a quick way by atmospheric motions and a long way by ocean currents. Obviously, anomalies transported by the atmosphere are short-lived, but properly averaged, they can interfere, or be in resonance with, long-term ocean transport, which has many spatial and temporal scales. A very important property of ocean–atmosphere interactions, hampering their modeling, should be emphasized: short-term (high frequency) anomalies in the atmosphere can lead to long-term (low frequency) consequences in the ocean and *vice versa* – long-term anomalies in the ocean can lead to short-term consequences in the atmosphere.

The most convincing results concerning relationships between the thermal state of the ocean and solar activity were reported by Tourre and White (1995) and White *et al*. (1998). They showed that decadal and interdecadal variability of depth-weighted vertical average temperature (from the sea surface to the top of the main pycnocline) are in phase across the Indian, Pacific, Atlantic, and global oceans, each significantly correlated with changing surface solar radiative forcing. They believe that the sum of solar radiative forcing and greenhouse effects can explain the sharp increase in global- and basin-averaged temperatures, but the proposed mechanism seems to be incomplete. First, the global average sea surface temperature response to changing solar radiative forcing is almost twice that expected from radiation balance. Second, the trend during the analyzed period has no explanation in the framework of the mechanism proposed, and was eliminated by means of filtration. Third, the depth-weighted vertical average temperature changes in the Indian, Pacific, Atlantic, and global oceans are correlated with changing surface radiative forcing at a lag of 0 ± 2 years. If we are looking for a cause and effect relationship, the negative lag at –2 years needs additional explanation beyond simple forcing by the change in surface solar radiation. The interesting results of Tourre and White (1995) show that anomalies of surface temperature and heat content in layers 0–400 m are opposite in phase (Figures 3.5.7 and 3.5.8).

Thereupon, we draw attention to interrelationships between the three systems: climate, solar radiation and ocean ecosystems. It is known that almost all climate-changing external (of solar and cosmic origin) and internal processes are accompanied by variations in electromagnetic (EM) and magnetic fields. Among the sun-attributed processes are integral radiation, flares, corpuscular flows, magnetic fields, and frequency spectrum fluctuations (especially in the high-frequency range). The biological effectiveness of EM fields is dependent on the wave length, and it is especially high in the range of ultraviolet (UV) irradiance (Aguilera *et al*., 1999). Relative fluctuations of this irradiance caused by different solar events can be an order higher than relative fluctuations of total solar radiation. Among different periods, characteristic for solar activity, UV has a quasi-biennial periodicity, reaching a maximum in years of the east phase and minimum in years of the west phase of El Niño Southern Oscillation (Troshichev and Gabis, 1998). The main effect of UV in the ocean is photo-inhibition, when considerable reduction in the photosynthetic capacity of a plant takes place. Different species of PP have different abilities to withstand UV-induced damage (the dinoflagellate *Noctiluca*, and *Fuchus distichus* as examples), and corresponding changes cannot only occur in the PP biomass, but also in the structure of plankton communities. Less damaged species have preferences among competitive species and produce exceptionally high biomasses, changing the water transparency. In that case, “red tides” might not be so much a result as the cause of El Niño.

Besides the light range 400–700 nm, responsible for photosynthesis, the biological effectiveness of EM fields is especially high in the extremely low frequency range 10^{11}–10^{12} Hz. A very high internal field in bio-membranes (100,000 V cm^{-1}) leads to a strong polar character in biological objects; oscillations in parts of the membrane become connected with electric vibrations. It has been shown that nonlinear coupling of elastic and electric polar modes and additional energy supply can create a quasi-ferroelectric behavior in cells that can explain extraordinarily high sensitivity of biological systems to extremely weak electromagnetic signals (Kaiser, 1982; Achimovicz, 1982). Coherent oscillations will lead to collective biochemical reactions through non-linear long-range interactions. Actually, we have here the non-thermal bioeffects of electromagnetic radiation: processes with energy much lower than needed for metabolism begin the trigger of macroscopic processes in living systems. The same is true for fluctuations in magnetic fields (some PP species can move along magnetic lines of the Earth). Such processes are treated as informational, and we can say that information, received by biological systems, controls their energy and mass interactions with environment. In this way, solar and galactic cosmic ray fluctuations can affect the enzymatic activity, metabolism and productivity of living matter on the Earth.

These effects can work at any trophic level, especially for the living matter continually exposed to radiation, that is, for PP. If an anomaly is forced at that level, the time of bottom-up changes will depend on the length of the trophic chain for the specific species, and it can be shorter than the time needed in the tropics or in other regions of originating anomalies to reach the area of high ocean–atmosphere energy exchange. On the other hand, synchronous externally-driven global changes can arise in populations of higher level consumers, and in this case we will observe top-down effects of ecosystem changes practically without, or with very short lags, relative to irradiative forcing.

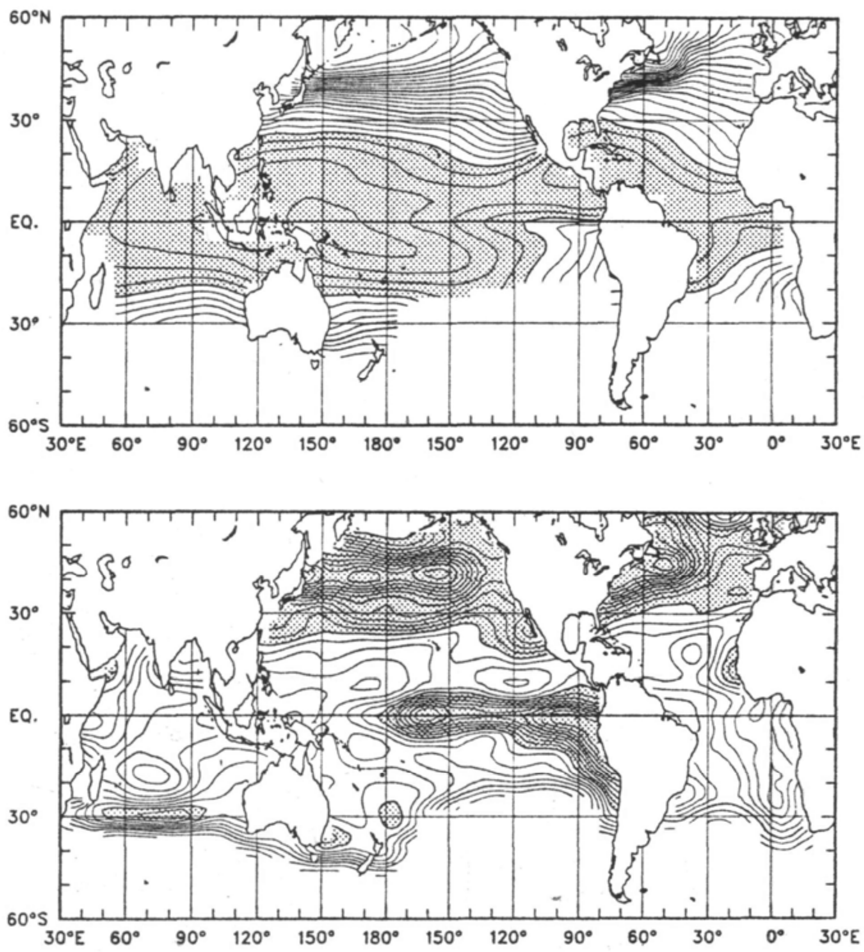

Fig. 3.5.7 (Top) Annual long-term means of sea surface temperature over the global ocean for the reference period 1979–1988. Values greater than 25°C are stippled. Contours are every 1°C. (Bottom) Standard deviation of SST anomalies over the global ocean for the 13-year period of interest from 1979–1991. Values greater than 0.5°C are stippled. Contours are every 0.05°C (from Tourre and White, 1995).

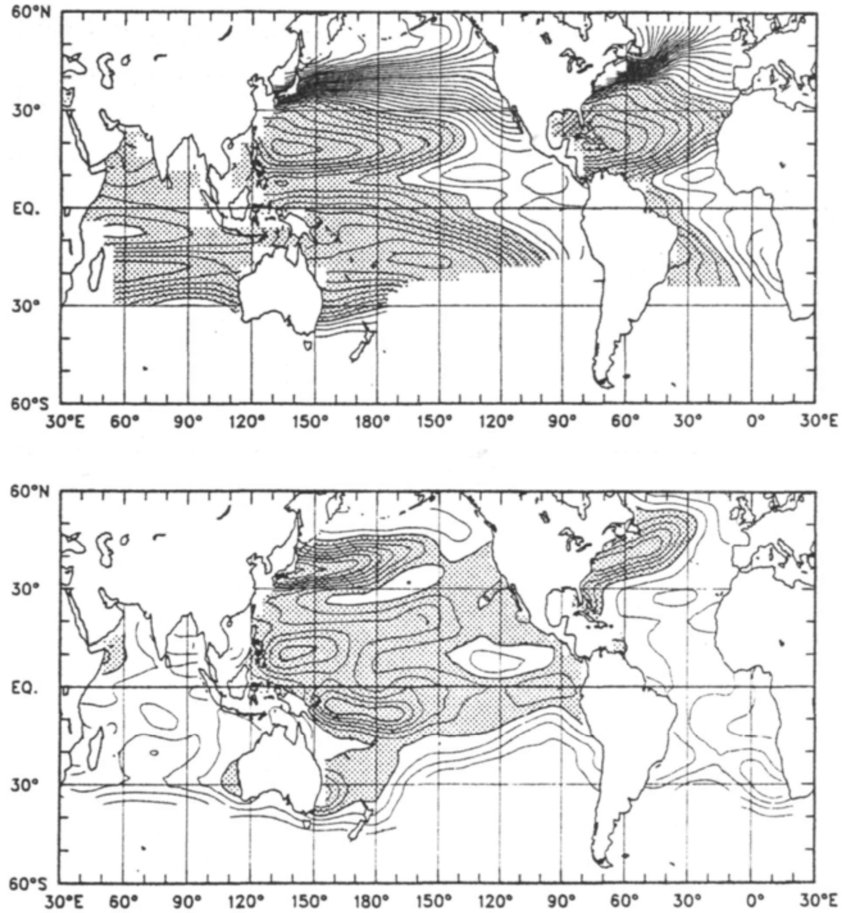

Fig. 3.5.8 (Top) Annual long-term means of heat storage in the upper 400 m (HS400) over the global ocean for the reference period 1979–1988. Values greater than 6×10^5 cal cm^{-2} are stippled. Contours are every 0.2×10^5 cal cm^{-2}. (Bottom) Standard deviation of the HS400 anomalies over the global ocean for the 13-year period of interest from 1979–1991. Values greater than 2×10^4 cal cm^{-2} are stippled. Contours are every 0.2×10^5 cal cm^{-2} (from Tourre and White, 1995).

Living matter is the only system on the Earth that can filter out thermal noise in specific frequency ranges and in this way, react to non-thermal impacts (that is, with energy lower than the thermal motion of molecules), which we treat as information flow. Some kinds of information also have lyotropic solutions because they can change their structure without changing chemical composition and thermodynamic state. Biological liquids are just lyotropic solutions with high sensitivity to extra weak fluctuations of the EM and magnetic fields, and they can be an additional means of having non-climate effects on living matter and a subsequent impact on living matter in the ocean on GC. We suggest that the whole World Ocean is to some extent a lyotropic liquid, and corresponding investigations would be useful.

Another mechanism of the EM-field fluctuation can be related to the fact that many marine organisms have specific EM and magnetic field perception. It is possible that just lyotropic biological liquids are responsible for such perception in the cases when no specific organisms can be found. Externally and internally forced large-scale fluctuations of EM and magnetic fields will change corresponding population behavior and ecosystem characteristics with the previously discussed consequences for climate. A generalized scheme of interactions in the Earth's climatic system, including mankind, is proposed in Figure 3.5.9.

We do not consider here actual anthropogenic impacts: they affect nature very unnaturally and are the objective of many investigations. However, it is clear that almost all kinds of human activity lead to additional input of radiation, pollution, chemical contamination, and to the degradation of the most necessary parts of nature – green living matter,

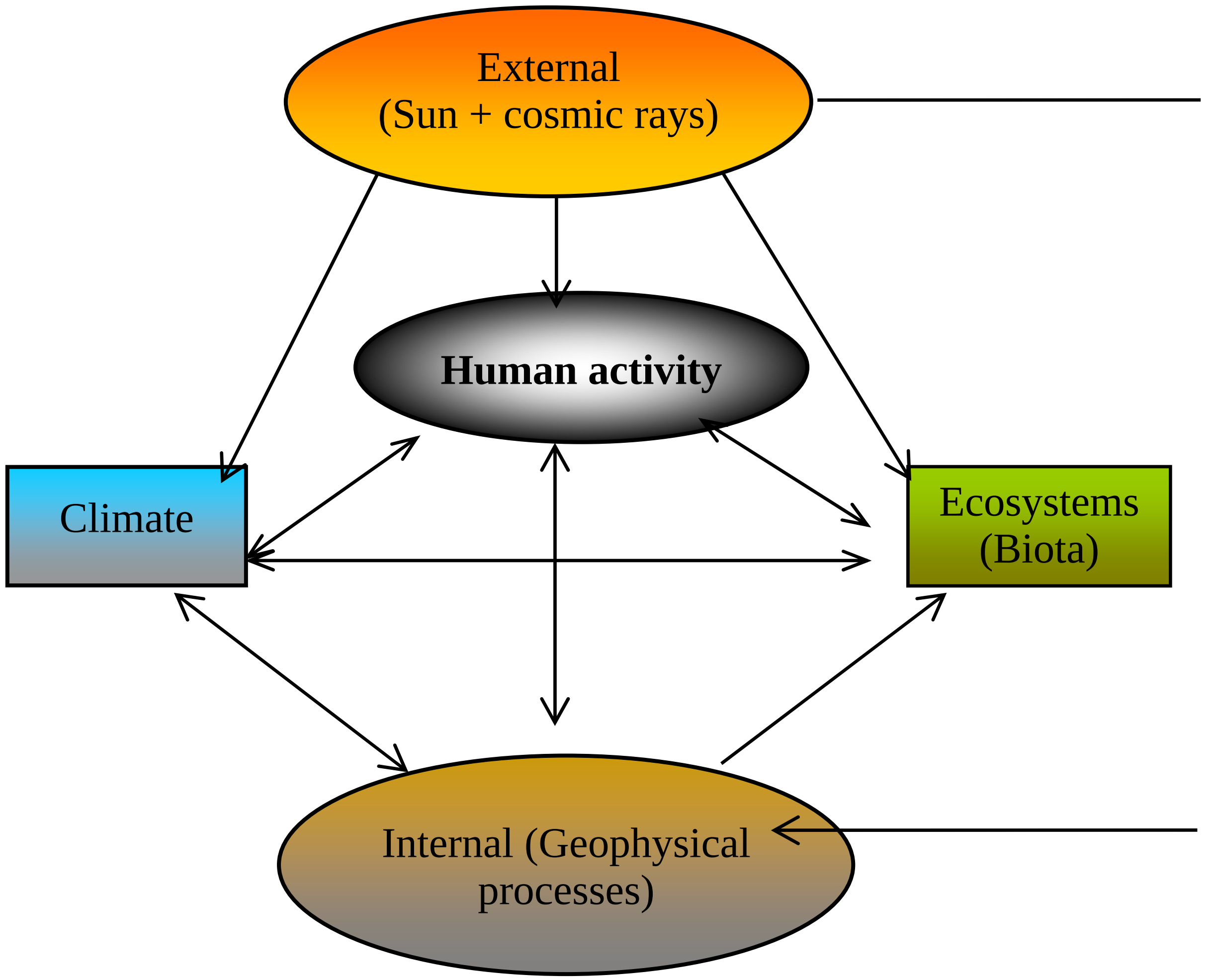

Fig. 3.5.9 Generalized scheme of interactions in the Earth's climatic system.

oxygen, and clear water. Our simple integrated scheme of the processes discussed in this paper shows that not only do all natural systems interact with each other in both directions, but all of them are influenced by human activity (as a rule, in a harmful direction). The only object in the scheme directly affecting everything, and not having any feedback from human activity is the Sun, but who knows?

Conclusions

- The World Ocean is the most important component of the Earth climatic system and the main contributor of energy for climate change. Its leading role in that system is due to its ability to accumulate solar energy and discharge it into the atmosphere with a very complicated space–time–amplitude distribution.
- Accumulating and discharging properties of the ocean are not constant. They fluctuate and change in time and space depending not only on the internal dynamics and state of the atmosphere and ocean–atmosphere interaction, but also on the state of living matter in the ocean. Living matter properties, in turn, are exposed to external sources for the ocean processes – mainly of solar, geophysical, and anthropogenic origin.
- As a result, to show the active role and significance of living matter in climate–ecosystem interactions, we should carry out investigations along both directions: sun–climate–ecosystems feedbacks and sun–ecosystems–climate feedbacks**.** It could be a closed circle, but is, in fact, unclosed by external forces which have very different effects (in time and space, in amplitudes and quality) on climate and ecosystems.

- Estimations of energy flow (see section on “Climate change and the World Ocean – Energy considerations”) show that it is very important and pressing to also investigate along the directions of human activity–climate–ecosystems feedbacks and human activity–ecosystems–climate feedbacks.
- Living matter can receive and react to signals with extremely low energy – informational flows – and in this way can control high-energy macroscopic processes. So future investigations should integrate detailed studies in different areas.
- The actual state of the Earth’s climate is characterized by the World Ocean overheating and continents overcooling, leading to exceptionally high evaporation, atmosphere circulation, and extreme spatial–temporal dispersions of all climatic parameters.
- The increase of green living matter on continents and in the ocean could diminish land–ocean contrasts, global ocean energy content, and lead to a moderate global climate.

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3.6 Evaluation of climatic variability in the Far-Eastern Seas using regional data sets and the relationship with large-scale climate processes

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Introduction

Recent Russian studies (Kattsov *et al.*, 2007; Meleshko *et al.*, 2007, 2008; Govorkova *et al.*, 2008; Assessment Report, 2008; Gruza and Ran'kova, 2009) show the difficulty in realistically simulating regional features of climate in the Far East of Russia by atmosphere–ocean circulation models (AOGCMs) presented in the Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC, 2007). The ensemble of AOGCMs successfully reproduces the seasonal cycle of air temperature, location and intensity of the Siberian High and Aleutian Low, and all the main climatic parameters, at least averaged over vast areas. However, the modeled trends of climatic parameters for the region do not coincide with the observational trends. Model ensembles show that the trends of air temperature are positive over the whole Far East region in all seasons, with maximal inclination in its northern part in winter. In contrast, observed trends of winter warming are strongest in the southern part of the region, but weak negative trends are observed over North-East Asia in winter, and strong positive trends in this area are observed in spring and autumn. These differences between modelled and observed climate changes are obviously caused by processes of regional scale and should be analyzed by regional models of high resolution. However, Russia still has no reliable high resolution model designed for the Far East and the Far-Eastern Seas. Essentially it is connected with a "fatal lack" of regular observations, and also with very complex physics of climatic processes on the ocean–continent boundary between North-East Asia and the North Pacific. Therefore, in preparing this report on climatic variability, we have given more attention to long-term sets of observed parameters that allow us to evaluate low-frequency variability in the Far-Eastern Seas. Possibilities of climate projections used to project marine ecosystem changes are considered as well, using the example of the Japan/East Sea.

Data and Methods

A set of parameters for climate change evaluation was chosen taking into account duration, uniformity and regularity of observations and significance for marine ecosystem research. The following sources were used:

- Time series of ice cover in the Okhotsk Sea in March (annual maximum) for 1929–1956 collected by Kryndin (1964) from various observations (shipboard, aircraft, coastal);
- Regular 10-day aircraft observations conducted by the Russian Hydrometeorological Service in the Okhotsk Sea in 1957–1991 and in the Bering Sea in 1960–1991;
- Satellite charts of ice cover obtained from the Far-Eastern Regional Center, Khabarovsk for 1992–1998 and from National Ice Center, U.S.A (http://www.natice.noaa.gov/pub/west_arctic) since 1998;
- Ice charts of the Okhotsk Sea distributed by the Japanese Meteorological Agency (for 2001–2010);
- Monthly mean air and water temperature data at coastal meteorological stations (Fig. 3.6.1) published by the Russian Hydrometeorological Service;
- Monthly mean air temperature data at meteorological stations collected in NASA GISS (http://www.giss.nasa.gov/data/update/gistemp).
- Sea surface temperature (SST) data from the Real Time Data Base of NEAR-GOOS (http://goos.kishou.go.jp/rrtdb) from 1950 to the latest month;
- Air temperature and sea level pressure data of the National Centers for Environmental Prediction (NCEP) reanalysis (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis).

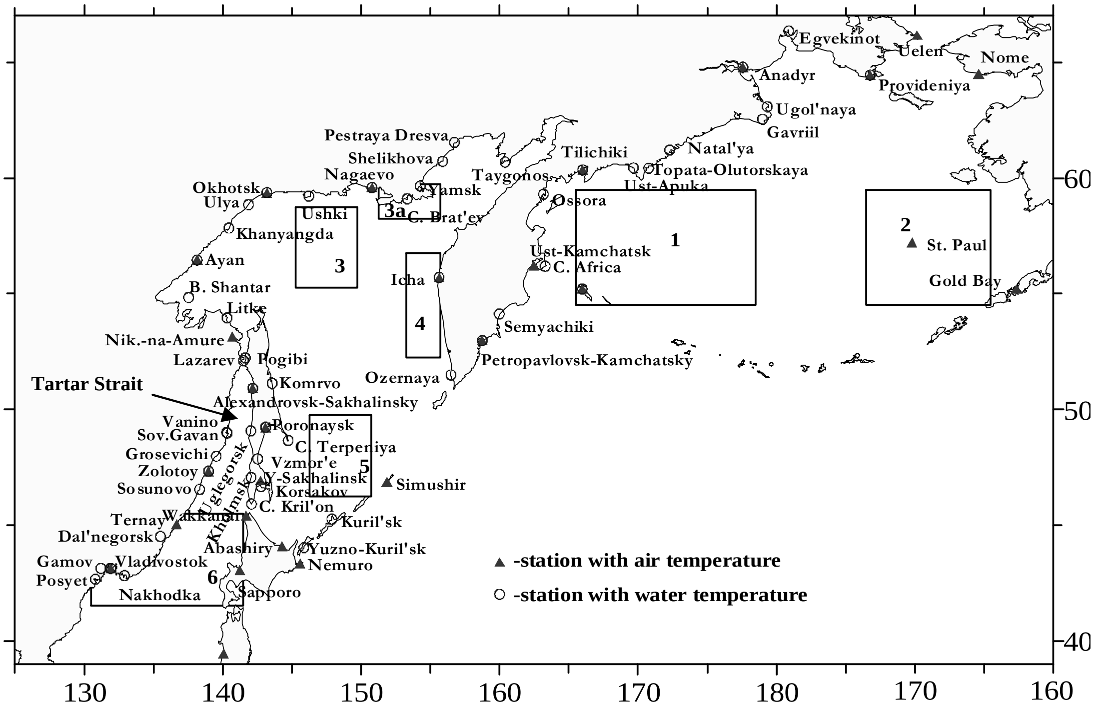

Fig. 3.6.1 Locations of meteorological stations in the Far Eastern Seas and North Pacific. Areas of regional averaging of sea surface temperature (SST) are numbered 1–6.

The longest time series are for the data on ice cover, and air and water temperature at meteorological stations. Sea ice extent was measured as the percentage of the ice-covered area from the total area of the Bering and Okhotsk seas and the Tatar Strait. These data were collected by 10-day periods, and mean winter ice cover was calculated by averaging for the period from January to April. For some purposes, the SST data were averaged within certain areas located in the Bering Sea (2 areas), Okhotsk Sea 3 areas), and Japan/East Sea (1 area) (Fig. 3.6.1).

Large-scale climatic indices (Aleutian Low Pressure Index (ALPI), North Pacific Index (NPI), Siberian High Index (SHI), Atmospheric Forcing Index (AFI), Pacific Circulation Index (PCI), West Pacific (WP), El Niño–Southern Oscillation (ENSO), Arctic Oscillation (AO), Pacific Decadal Oscillation (PDO) and Victoria indices, global and Northern Hemisphere averaged surface air temperature; macro-scale pressure gradient between the Siberian High and Aleutian Low) were used from the following sources:

- Monthly mean global and Northern Hemisphere air temperature anomalies data from http://www.cru.uea.ac.uk/cru/data/temperature/ (Brohan *et al.*, 2006).
- Climatic indices from:
  - http://www.beringclimate.noaa.gov/data/index.php,
  - http://www.cgd.ucar.edu/cas/catalog/climind/,
  - http://www.cpc.ncep.noaa.gov/products/,
  - http://jisao.washington.edu/,
  - http://www.pac.dfo-mpo.gc.ca/sci/sa-mfpd/climate/clm_index.htm;
- Victoria winter Pattern: the second EOF from an analysis of winter SST (Bond *et al.*, 2003).
- Macro-scale pressure gradient between the Siberian High and Aleutian Low and intensity of the Far-Eastern centers of atmospheric action (by Vasilevskaya *et al.*, 2003).

The indices were used in many studies devoted to climatic variability (*e.g.*, Mantua *et al.*, 1997; Thompson and Wallace, 1998; Wolter and Timlin, 1998; Bond and Harrison, 2000; Miller and Schneider, 2000; Schneider *et al.*, 2002). In addition, data on the frequency of regional atmospheric circulation types determined by Glebova (1999) were used. This classification of regional circulation is based on the mutual arrangement of high and low atmospheric pressure centers and prevailing winds.

All data were analyzed by standard statistical methods. For each parameter, annual values were normalized by subtracting the average of all years and dividing by the standard deviation. Measures of climate variability and covariability (variances, covariances, correlations, coherency, standard deviations, anomalies, spectra, extremes, *etc.*) were estimated with a statistical significance level ≥ 95 %.

Evaluation of Low-Frequency Variability of the Thermal Regime in the Far-Eastern Seas

Consistent estimations of regional climatic trends in air temperature have been made by many investigators (Kim *et al*., 1997; Varlamov *et al*., 1998; Pestereva and Pushkina 1998; Ponomarev *et al*., 2000, 2002, 2005, 2007; Assessment Report, 2008) from observations collected by Russian meteorological stations. Principal features of these trends are:

- strong irregularity and inhomogeneity in time and space connected with specific macro-circulating atmospheric processes on the boundary between the Eurasian continent and the Pacific Ocean;
- maximal trends to warming in winter and spring in the southern part of the region (Primorye, Japan, southern Kamchatka) and in spring, summer and autumn over Chukotka;
- weak negative trends in the areas to the north from the Okhotsk Sea and to the west from the Bering Sea in winter;
- tendency to decreasing differences between summer and winter air temperatures in the Japan/East Sea and increases in the northwestern Okhotsk Sea; *i.e.*, the continentality increases in the northern part of Far East and decreases in its southern part.

Sea ice cover in the Okhotsk Sea shows a negative trend both for mean winter values (for 1957–2010; p = 99.9 %; Fig. 3.6.2) and annual maximums (1929–2010; p = 95 %; Fig. 3.6.3), but in the Bering Sea and the Tatar Strait, its negative trends are not statistically significant. The time of annual maximum has no significant trends in the Okhotsk and Bering seas; generally, it is stable in the Okhotsk Sea and highly variable in the Bering Sea (Fig. 3.6.2, right). Correlations between annual maximum ice cover and its date are not significant, although usually the earlier the maximum in the Bering Sea, the lower the ice amount.

Ice cover fluctuations show a remarkable feature: their phases are opposite between the Okhotsk and Bering seas (Yakunin, 1966; Khen, 1997; Plotnikov, 1997, 2002). However, after a long period of anti-phase variability, the ice cover in these seas began to fluctuate synchronously starting in the late 1980s (Fig. 3.6.4). Recently, ice extent has been decreasing in the Okhotsk and Japan/East seas: the last severe winter in these areas was in 2000–2001, and the ice extent has been low during the last 6 years, with an absolute minimum of mean winter ice cover in 2009 (38%) in the Okhotsk Sea. Recent changes in ice cover in the Bering Sea have a positive tendency, and its year-to-year variations are opposite to that of the Okhotsk Sea, again, with a high ice cover percentage in 2009 (36.5 %). The frequency of extreme situations has increased during the last 15 years in the Okhotsk Sea.

Spectral analysis of the longest time series for maximum ice cover in the Okhotsk Sea shows that a quasi-pentadecadal oscillation makes a basic contribution to the variance (Fig. 3.6.3, right). This oscillation is known as well for air temperature at some Far-Eastern meteorological stations (Ponomarev *et al.*, 2003; Ustinova and Shevchenko, 2004), for winter–spring sea level pressure over the North Pacific (Minobe, 2000), and for globally averaged air temperature (Klyashtorin and Lyubushin, 2003). Other important contributions are oscillations with periods of 10, 18, and 25 years. For the updated time series with recent years, the contribution of the quasi-pentadecadal and 25-year components has decreased relatively, but the contribution of the 10-year scale has increased. The shorter powerful oscillation in the Okhotsk Sea has a period of 7 years, noted by Plotnikov (1997, 2002). In the Tatar Strait, shorter cycles have prevailed, but on the whole, the periodical components are represented weakly. The spectrum for the Bering Sea has strong oscillations with periods of 4–5 and 10 years. In general, the contribution of low-frequency components is the highest (74 %) for the Okhotsk Sea and the lowest (30 %) for the Tatar Strait. The physical mechanisms of these oscillations are not quite clear yet.

SST variability at coastal meteorological stations is determined partially by air conditions but depends on local oceanographic processes as well. That is why it is characterized by a small radius of spatial correlation after removing trends (Ustinova *et al.*, 2001). Even long-term trends can be opposite at closely spaced coastal stations, *e.g.*, in Peter the Great Bay (Gayko, 2007) because of the effects of local currents and upwelling. However, in general, trends to warming are clearly expressed in winter and spring at many stations in all the Far-Eastern Seas. (Note that the SST variability in winter is small at the meteorological stations in the Okhotsk and Bering seas, covered by sea ice, so it cannot serve as an indicator of climatic changes; moreover, some stations stop SST observations in winter). Besides, positive trends of spring SST have been found in areas 3–6 (Fig. 3.6.1) of the Okhotsk and Japan/East seas. In contrast, SST trends to cooling prevailed in the Okhotsk and Japan/East seas and northwestern Pacific in summer until the end of 20th century (Ponomarev *et al.*, 2005). The tendency to summer cooling has finished recently in the Okhotsk and Bering seas (Khen and Sorokin, 2008).

Spectra of air and water temperature obtained from meteorological station data show a significant contribution of high-frequency oscillations (quasi-biannual and ENSO scales) while the major part of variance of ice cover is formed by low-frequency oscillations with periods about a decade and more (Fig. 3.6.2, right). This means that the sea ice is a "natural filter" of high-frequency variability.

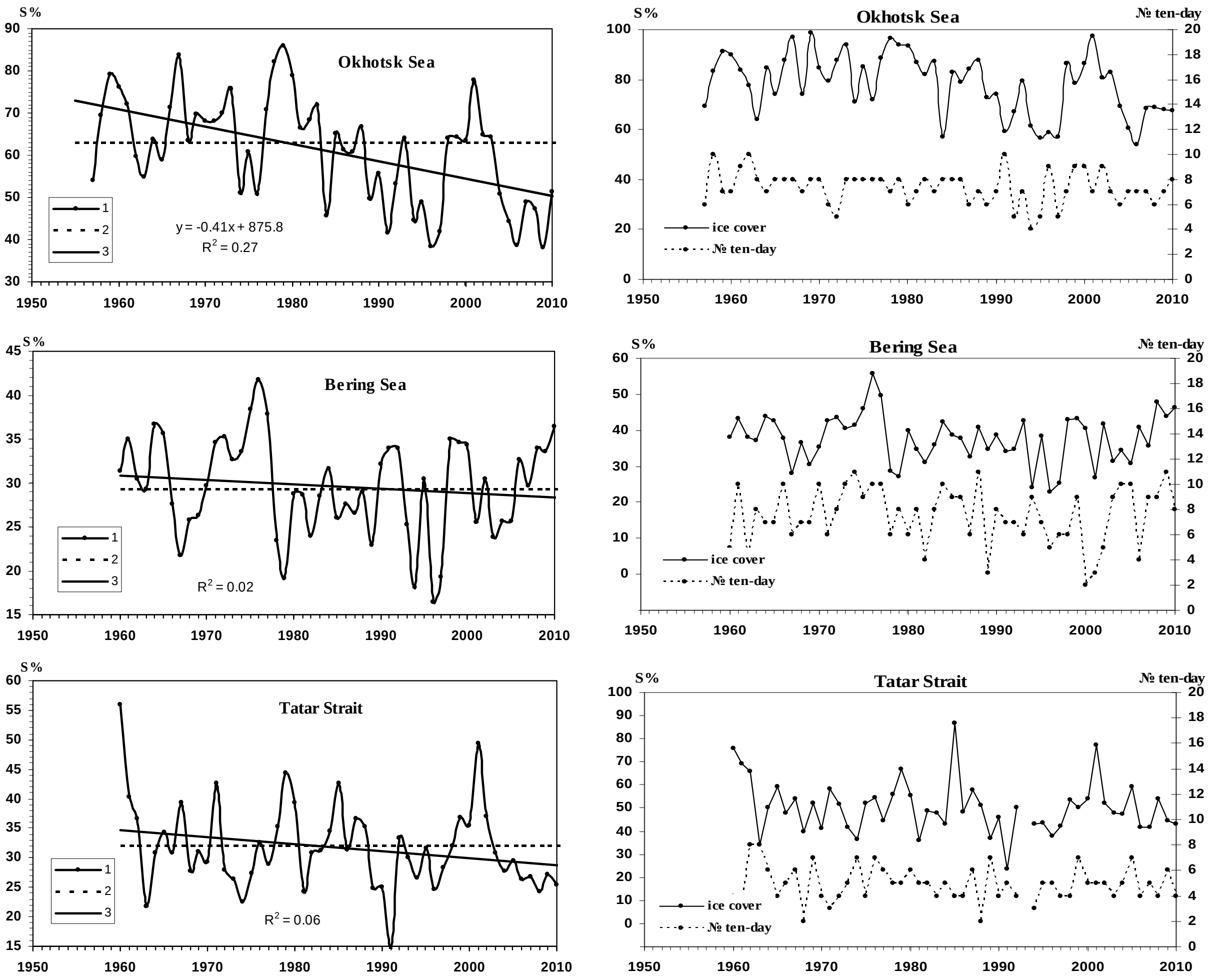

Fig. 3.6.2 (Left) Mean winter (January–April) ice cover (1), mean multi-year value (2), and linear trend (3). (Right) Annual maximum ice cover and its terms (number of 10-day periods from the beginning of the year) in the Far-Eastern Seas. "S" is % to the total area of the sea (updated from Ustinova *et al.*, 2008).

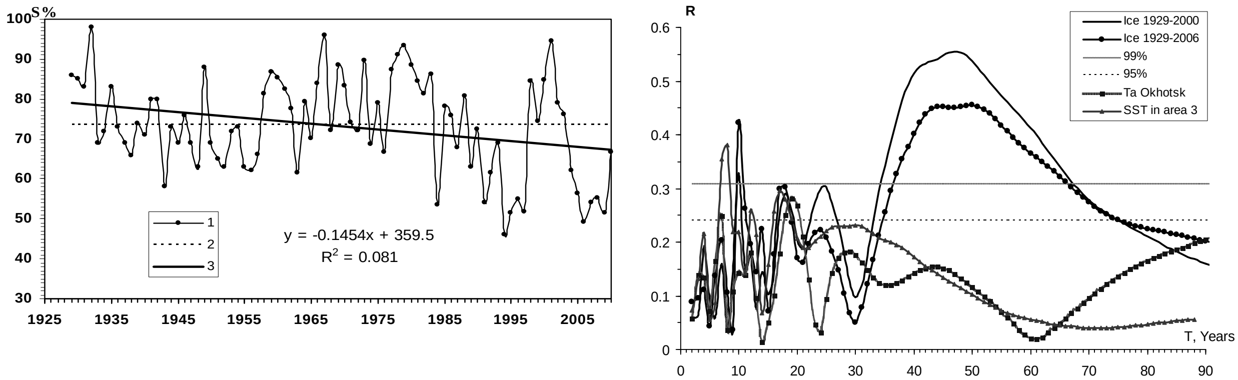

Fig. 3.6.3 (Left) Annual monthly mean maximum ice cover (in March) of the Okhotsk Sea (1), mean multi-year value (2), and linear trend (3). "S" is % to the total area of the sea. (Right) Correlations between annual maximum ice cover of the Okhotsk Sea for the time series: 1929–2000 and 1929–2008, winter air temperature in Okhotsk, spring SST in area 3, from Fig. 3.6.1, and its periodic components (updated from Ustinova and Sorokin, 2009).

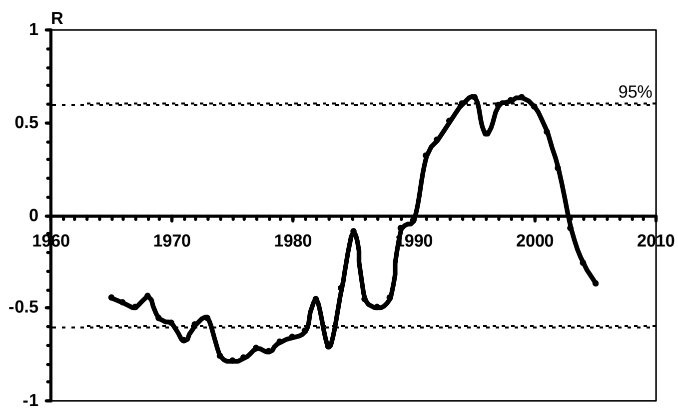

Fig. 3.6.4 Eleven-year "running correlation" of the mean winter ice extents in the Okhotsk Sea and Bering Sea.

SST anomalies in the warming season (March–June) show a remarkable spatial coordination with mean winter ice cover in the Okhotsk and Bering seas (Fig. 3.6.5). There is a negative correlation between SST anomalies and ice cover in the Bering Sea over a large area from Kamchatka to the North American coast, along this coast and in the tropical zone, but the correlation is positive in the Kuroshio, eastward from the Kuril Islands and in the central North Pacific. These "U-shape" patterns are almost stable from March to June. The picture is similar but less clear for ice cover in the Okhotsk Sea (Fig. 3.6.5).

The Relationship of Regional Variability with Large-scale Climate Processes

All large-scale changes of the thermal regime in the Far-Eastern Seas are connected somehow with the global and hemispheric processes in the atmosphere and ocean. However, regional processes modify the global impact considerably. The linkages between large-scale climatic processes and regional conditions in the Far-Eastern Seas are different for various temporal and spatial scales. For example, ice cover variations in the Okhotsk and Bering seas correlate well with variations of winter air temperature anomalies in the northern hemisphere for the time scale >7 years (R = –0.71 and –0.48, respectively) because of similar trends and quasi-pentadecadal contributions (see Fig. 3.6.6, left), but the correlation becomes insignificant after filtration of these long-term components. Ice cover and SST in the Far-Eastern Seas have no strong correlation with the majority of climatic indices, with only a small exception (Khen *et al*., 2008). Our results for linkages of ice cover in the Bering Sea and NPI and WP index are similar to the results of Niebauer *et al.* (1999). The WP index characterizes a north–south dipole over the western North Pacific and influences the ice cover in the Okhotsk Sea more than in the Bering Sea. Indices connected with parameters of the Aleutian Low and PDO are more important for the Bering Sea then for the Okhotsk Sea. The Victoria SST pattern is more representative for ice cover in the Okhotsk Sea than the PDO, R = 0.54 (0.62 after filtering quasi-2-year oscillations). For the Bering Sea the correlation is less, R = 0.31 and 0.36, accordingly. Since 1993 this index has changed synchronously with ice cover both in the Okhotsk Sea and in Bering Sea (Fig. 3.6.6, right). Before this period, a contrast prevailed in oscillation phases of the ice cover in the Bering Sea and Victoria index. The AO index and macro-scale pressure gradient between the Siberian High and Aleutian Low, as a winter monsoon index, are important for climatic parameters in the Okhotsk and Japan/East seas.

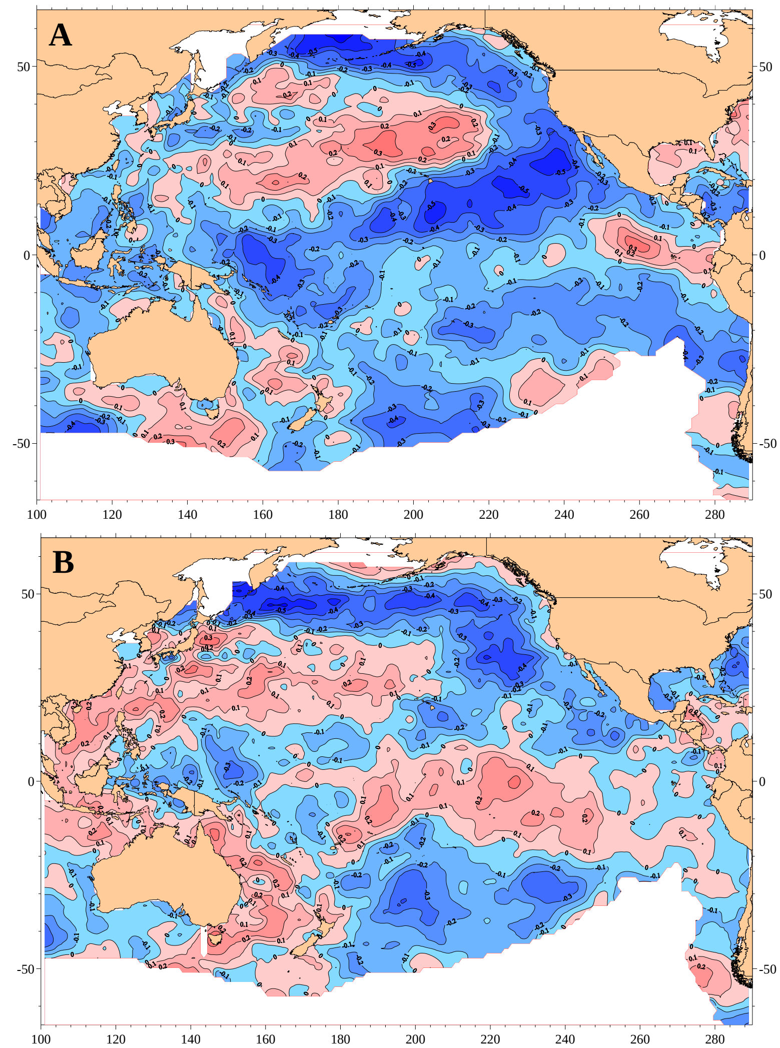

Fig. 3.6.5 Correlations R between mean winter ice cover in (A) the Bering Sea and (B) Okhotsk Sea and SST anomalies in March. Negative correlation is blue. Areas of significant correlation are dark blue and dark red, $R_{95\%} = 0.29$ (updated from Ustinova and Sorokin, 2005).

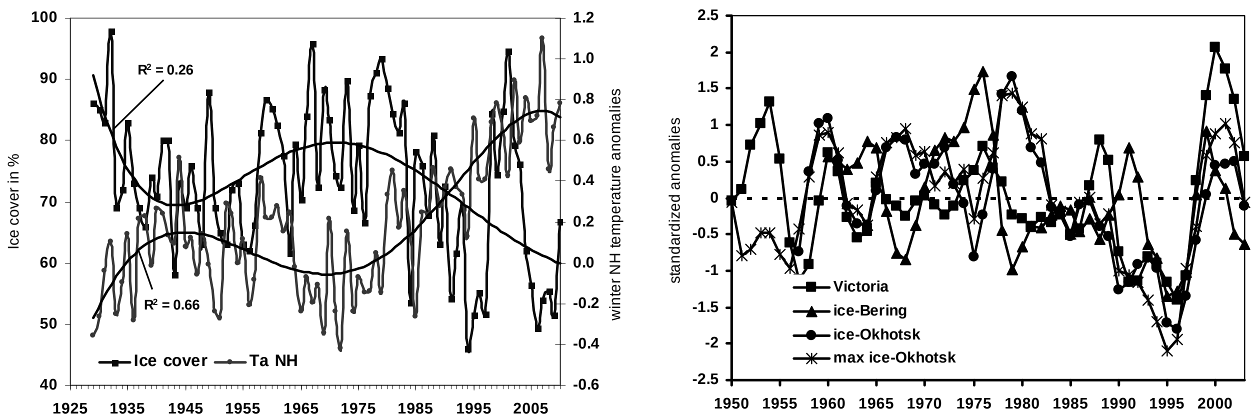

Fig. 3.6.6 (Left) Winter Northern Hemisphere temperature anomalies, annual maximal ice cover in the Okhotsk Sea and its polynomial trends. (Right) Victoria Index (winter), mean winter ice cover in the Okhotsk and Bering seas and maximal ice cover in the Okhotsk Sea (standardized and smoothed by a 3-year running mean).

The highest correlation is found between the ice extent and SST in the Far-Eastern Seas and the frequency of winter types of regional atmospheric circulation proposed by Glebova (1999). The frequency of types IV (cold) and VI (warm) for the Okhotsk Sea corresponds strongly with the mean winter ice cover in the Sea, and the correlation is positive in the former case and negative in the latter. The frequency of some of Glebova's other types is connected with the variability of SST anomalies in certain areas.

Stability of the relationships is analyzed by statistical methods, with emphasis on cases when the connections change from positive to negative and *vice versa*. "Running correlations" are used to reveal significant changes in the relationships (Fig. 3.6.7). The steadiest relationships are found between WP index and regional SST and ice cover. Obviously, the Far-Eastern troposphere trough reflected by the WP index determines regional conditions in many aspects. However, the correlation between the winter WP index and ice cover in the Okhotsk Sea decreased sharply in the early 1980s and after recovering in the early 1990s, started to decrease again in 2006. For the period 1976–1987, the correlation between mean winter ice cover and the Victoria pattern was insignificant. It is known that since 1990, the role of the Victoria pattern has increased in comparison with the PDO (Bond *et al.*, 2003), and the index changes synchronously with ice cover in the Okhotsk Sea. Correlation between the multivariate ENSO index and ice cover in the Okhotsk Sea tended to decrease after the climate shift in 1977. During the last few years the correlation has declined to near zero values. Pronounced reorganizations of the relationships with accompanied inverse (for example, between ice cover in the Okhotsk Sea and AO/PDO, winter SST in the Japan/East Sea and AO) correspond to the well-known 1976/77 and 1988/89 regime shifts (*e.g.*, Hare and Mantua, 2000; Bond *et al.*, 2003; Rodionov and Overland, 2005) most often. Similar changes of "global–regional linkages" depending on climatic regimes were found by Ponomarev *et al.* (2008, 2010) for some regional climatic variables (*e.g.*, amplification of the AO effect and weakening of the winter ENSO signal in the western subarctic area). The longest periods of relatively stable linkages were found for winter SST in the subtropical region of the Japan/East Sea and ENSO and WP indices (Fig. 3.6.7). Analysis of the changes in the relationships within regimes (from one regime shift to other) has shown that the quasi-steady state of the climatic system can be broken locally in the Far-Eastern Seas because of moving climatic atmospheric and oceanic fronts, trajectories of cyclones, change of blocking processes, and other boundary phenomena.

Regional features of climatic variability in the Far-Eastern Seas show potential difficulties for statistical downscaling in this region mainly due to:

- insufficient data supply (number of meteorological stations in Siberia and the Russian Far East has decreased since 1992, and there was a coarseness of the observational network in these regions initially);
- local "sub-grid" physical processes;
- instability of relationships between regional parameters and large-scale patterns.

Whereas statistical downscaling assumes that the relationship between predictors (large-scale variables) and predictions (small-scale variables) does not vary under climate change conditions, the relationship between regional parameters (such as sea ice coverage, air and water temperature) and large-scale climatic indices is very unstable. The method of atmospheric circulation typing (*e.g.*, created by Glebova (1999) for the Far-Eastern Seas) allows one to decrease some limitations in these regression models. However, this method requires the additional task of classification. Obviously, further detailed fundamental studies of regional climatic systems are necessary to better understand the processes of their variability. Reasonable development of observational systems in the region is also very important.

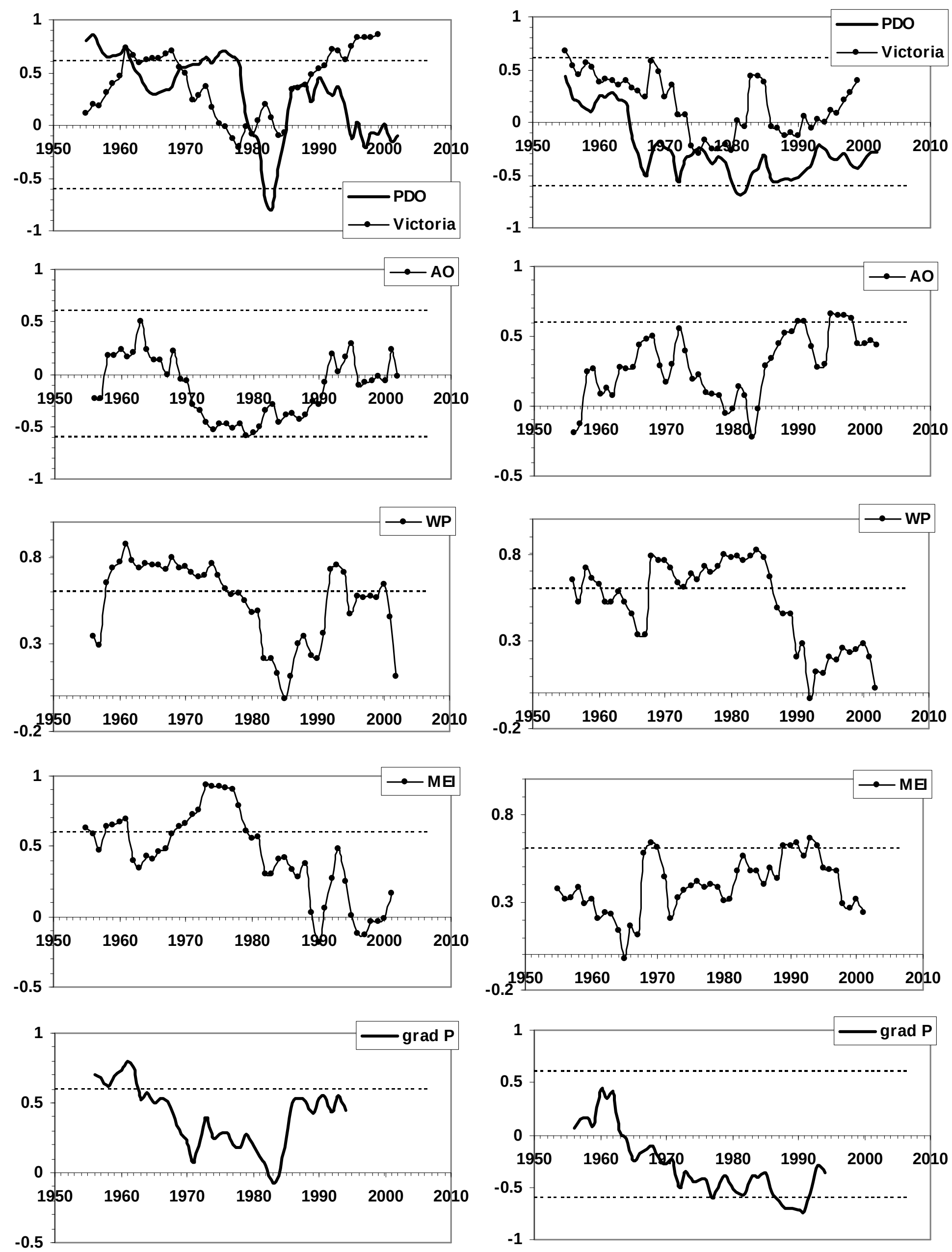

Fig. 3.6.7 "Running correlation" with 11-year period between annual maximum ice cover in the Okhotsk Sea (left), winter SST in the southern Japan/East Sea (right), and winter large-scale climatic indices (dashed line is 95% confidence level) (Ustinova and Sorokin, 2009). PDO = Pacific Decadal Oscillation, AO = Arctic Oscillation, WP = West Pacific index, MEI = Multivariate ENSO Index, grad P = macro-scale pressure gradient between the Siberian High and Aleutian Low.

Possibilities for Using Climate Projections to Predict Marine Ecosystems Changes: A Case of the Japan/East Sea

In so far as long-term climate projections are a relatively new scientific product that still has some novelty but is not actually useful, they are still not strictly demanded in practice. Now it is feasible to consider mostly the possibilities of adapting these projections to marine ecosystems but not scenarios of climate change influence. These possibilities depend on the scale of natural processes and so, on the depth of the projected downscaling. Note that the crux of downscaling is not a decreasing of the projection scale or heightening of its resolution, but on taking into consideration the involvement of sub-scale processes. That is why projections of different scales operate with different sets of processes, and the success of forecasting depends strongly on the basic knowledge of these processes, both in the climate system and ecosystem.

Theoretically, the variability of ecosystems could be caused by both external and internal factors, which strongly complicates the problem of their projected changes. Fortunately, the long-term changes usually look as environmentally forced ones, which allows us to consider marine ecosystem changes as a cause-and-effect chain: climate changes–their effect on ecosystems. Using this assumption, the procedure of applying climate projections to changes of an ecosystem includes three steps:

1. climate changes projection,
2. downscaling of the climate change projection to the scale of ecosystem or its components,
3. interpretation of the climate changes in terms of the ecosystem or its components using the relationships between abiotic and biotic parameters of the ecosystem.

In the case of the Japan/East Sea, both “regional” steps (downscaling and interpretation) are problematic because both physical and biological processes have still not been investigated in detail here. However, current knowledge allows us to outline the main consequences of climate change for local environments and marine biota with, of course, some uncertainties depending on scale.

For the Japan/East Sea ecosystem (basin-scale), it is reasonable to also consider the processes of larger and smaller scales, namely: regional-scale, basin-scale, mesoscale, and sub-mesoscale ones because all of them could have an influence on the ecosystem and its parts or components. In the following we discuss what the possibilities of climate projection applications are for this ecosystem on these scales.

Regional scale

The main processes on a regional scale (determining environmental conditions in the region of North-East Asia–Northwest Pacific) are monsoons: winter and summer ones. This level of downscaling is already realized in IPCC models as continental projections, including the projections of air temperature and precipitation, but not wind rates. On the other hand, monsoon winds cannot influence marine ecosystems (except for birds) directly – they do it through certain mechanisms of air–sea interaction at lesser scales.

Basin scale

The most important basin-scale processes are those which form water masses of the Japan/East Sea: advection of subtropical water; convection (deep and slope), subduction – the first forms the surface waters, the second – the subsurface, deep and bottom waters, and the third – the intermediate waters. These processes are only partially included in the global IPCC models, but could be modeled in existing regional models on the basis of regional-scale IPCC projections as initial conditions because they are determined by air–sea interactions. Note that winter conditions are more important on this scale because convection and subduction occur in winter (Fig. 3.6.8). Wind stress estimations are necessary for correct modeling of all these processes, so poor or absent projections of wind could be a source of uncertainties in the projections of advection, convection, and subduction and therefore, in the projections of water mass conditions.

Following the models and observations in the last decades, we see that recent winter warming in North-East Asia (that is projected for the 21st century, as well) causes prominent changes in the intermediate, deep, and bottom layers because of convection weakening. For the deep and bottom waters, it means warming, deoxygenization, and nitrification; for the intermediate water – warming, freshening, and enrichment by oxygen; and surface waters become less productive (Zuenko, 2008). On the other hand, summer warming does not have consequences so far, though it contributes to warming of the surface layer.

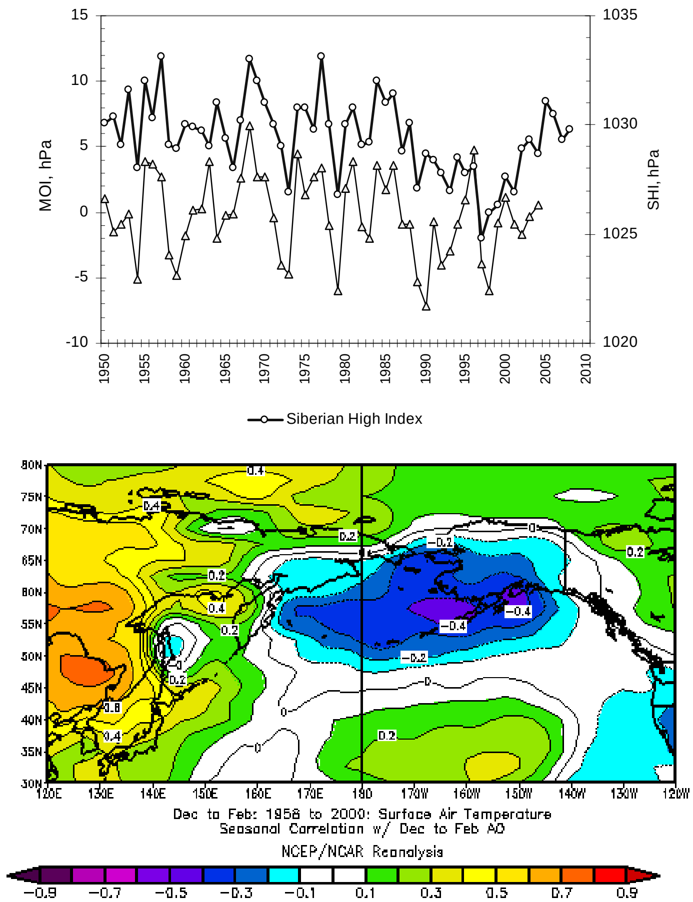

Fig. 3.6.8 (Top) Changes of the Siberian High Index (SHI, from Panagiotopoulos *et al.*, 2005, with additions) and Winter Monsoon Index (MOI, from Tian *et al.*, 2008). (Bottom) Correlations of surface air temperature in December–February with the winter Arctic Oscillation (AO) index (Wu and Wang, 2002). The Japan/East Sea is the only basin in the Northwest Pacific that has a strong positive relationship with the AO index and therefore, negative relationships with SHI and MOI. Tendency to a lowering of winter atmospheric pressure over Siberia prevails in the last decades, which causes warmer winters over the Japan/East Sea and weaker stress of winter monsoon winds on its surface.

Besides productivity, the projected environmental changes will directly influence some components of the ecosystem, in particular the reproduction of some animals. One of the most prominent consequences of recent warming in Intermediate Water is the increase of zooplankton abundance because of an increase in large-sized copepod biomass (Fig. 3.6.9). These species mature and spawn in the intermediate layer, and its warming is obviously favorable for them (note that the Intermediate Water of the Japan/East Sea is extremely cold, compared with other seas).

The surface layer temperature conditions influence the reproduction and distribution of many fish species, both directly and through feeding resources. For example, the maturation of winter-spawning fish species depends on temperature in winter (the warmer the water, the faster the maturing, the earlier the spawning), but the timing of the spring phytoplankton bloom depends on the temperature in spring (the warmer the water, the earlier the blooming). Depending on the relative changes in the environment in certain seasons, climate change could cause a match or mismatch of the larvae hatching with their prey bloom. So the projected winter warming may be unfavorable for some species, as happened with saffron cod in the 1990s when the period between its spawning and plankton bloom was too long. However, the tendency to warming is favorable for warm-water species which have the ability to expand over the whole basin of the Japan/East Sea.

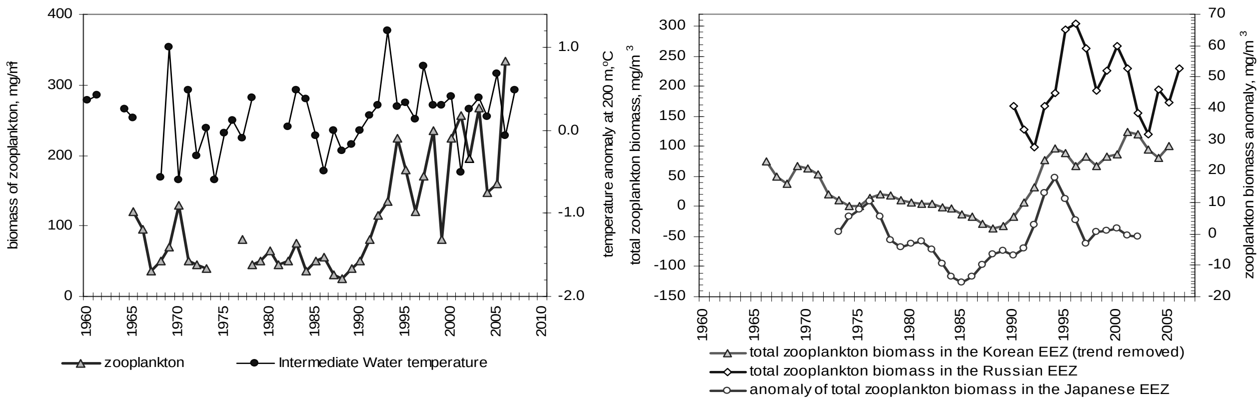

Fig. 3.6.9 Change of the total annual mean zooplankton biomass in the southwestern Japan/East Sea (left) and other parts of the Sea (right, smoothed). The left graph is compared with anomalies of winter temperature of the Intermediate Water in the same area (Rebstock and Kang, 2003; Zuenko *et al.*, 2010).

Mesoscale

Mesoscale processes occur at natural boundaries of the sea, *e.g.*, its coasts, shelves, fronts between water masses, mixed layers at its surface and bottom. Some of these processes can be modeled in existing models as initial conditions on the basis of regional-scale (monsoons) and basin-scale (advection) projections, but others cannot; actually, their predictability is conditioned by knowledge of their driving mechanisms. Even for well-studied processes, the uncertainty of their predictions is higher in comparison with basin-scale ones because predictions of the former are based on predictions of the latter ones. The mechanisms of mesoscale processes' influence on components of the marine ecosystem are known in some cases and vague in others, so their influence on the ecosystem could be projected sometimes. For example, zooplankton composition in the coastal zone (in Peter the Great Bay) could be projected on the basis of monsoon wind projections because the portion of deep-water species in the coastal zone depends strongly on monsoon activity: some species are transported into the coastal zone within the surface layer by on-shore currents driven by summer monsoons; others are advected in the subsurface layer by an on-shore compensatory current of upwelling circulation driven by winter monsoons (Fig. 3.6.10). Obviously, the projected weakening of winter monsoons contributes to a separation of the coastal zone from the deep-water sea, so its species composition in fall–winter will be poorer (at the expense of subtropical species), but relatively stable summer monsoons will provide a species diversity of summer zooplankton in the coastal zone, with some decadal and year-to-year changes, as those shown at Figure 3.6.10.

Sub-mesoscale

Principles of sub-mesoscale processes involving long-term projections are unclear yet. Some, having small spatial scales, are driven by mechanisms similar to mesoscale ones, as propagation of estuarine plumes or tidal fronts, so they can be projected in similar ways, but most of them (for example: internal waves, estuarine filters, fine structures) have a completely different nature, in which the relation to climate changes is unknown. Thus, only few sub-mesoscale processes are accounted for in local models of climate change, and these models have to be verified repeatedly for each new area. Uncertainty of the sub-mesoscale processes projections tends to infinity, so including these processes into climate projections needs to be preceded by detailed studies of them. Other detailed studies are necessary for understanding the sub-mesoscale processes' influence on marine ecosystems.

In general, the ability to apply climate change projections to marine ecosystems depends strongly on our knowledge about the mechanisms of the environment's influence on ecosystems at different scales, and about the physical process at different scales. Uncertainty of these projections definitely grows with the lowering of scale level, and for the Japan/East Sea, it becomes unacceptable on the sub-mesoscale level (Table 3.6.1). However, a projection is possible for the basin scale. Fortunately,

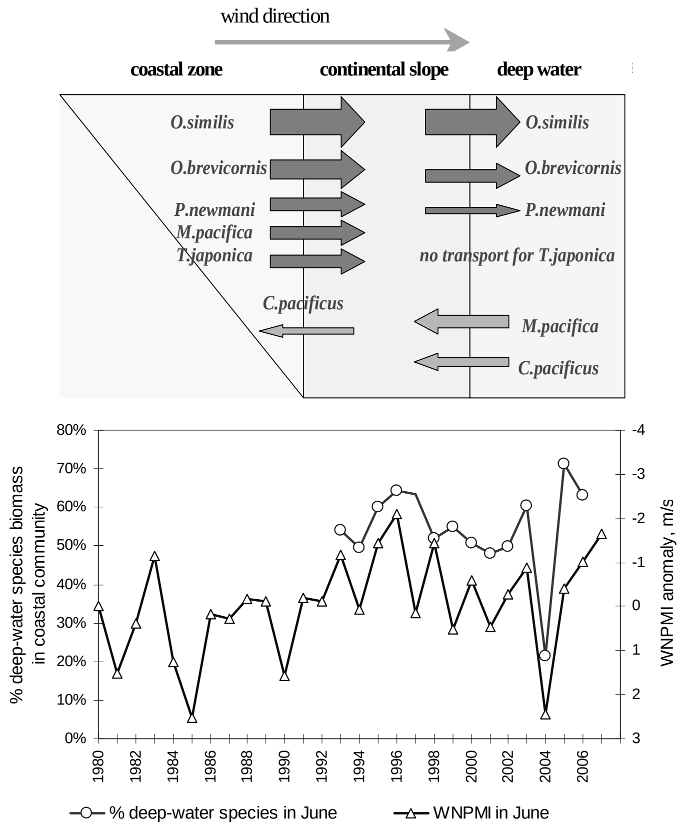

Fig. 3.6.10 Scheme of zooplankton species transport by cross-shelf circulation driven by winter monsoons (top) and year-to-year changes of deep-water species abundance in the coastal zone in summer under the influence of summer monsoon changes (bottom) illustrated by the West-North Pacific Monsoon Index (WNPMI; from http://iprc.soest.hawaii.edu/) (Zuenko *et al.*, 2010).

Table 3.6.1 Possibilities for climate projections applied to marine ecosystems in the Japan/East Sea.

Scale	Basis	Possibility of projecting	Uncertainty	Trophic levels that can be projected	Examples of projections
Basin	Existing models on the basis of IPCC projections	Possible on existing knowledge	Low	▪ Primary production ▪ Zooplankton ▪ Nekton (species)	▪ Potential PP model ▪ Zooplankton biomass model ▪ Saffron cod stock model
Meso-	Existing models on the basis of IPCC projections and basin-scale projections	Possible on existing knowledge for some processes	High	Zooplankton	Zooplankton species composition in coastal zone
Sub-meso-	Insufficient	Poor	Unacceptable	Nothing	No examples

the projections on this scale are the most claimed in practice, in so far as they concern such practically important parameters of marine ecosystems as biological productivity, food base, and commercial resources, whereas the parameters determined by the processes of finer scales, regarding mostly the distribution of marine organisms, are less important.

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3.7 Up- and down-scaling effects of upwelling in the California Current System

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Background

Though global climate models can represent many identifiable features of the climate system, they also suffer from significant localized biases. Climate model biases are not uniform over the globe. For example, in the ocean, modeled sea surface temperature (SST) errors are often largest along the continental margins (Fig. 3.7.1). Many coupled climate models generate very large SST biases in the coastal upwelling regions of the California Current System (CCS), the Humboldt Current system (HCS) and the Benguela Current System (BCS), where simulated mean SSTs are much warmer than observed. Figure 3.7.1 (top left panel) shows that the U.S. National Center for Atmospheric Research Community Climate System Model 3 (NCAR-CCSM3 spectral atmosphere) used in the Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC-AR4) was no exception, with biases in excess of 3°C in all three regions. Furthermore, these SST biases have significant remote effects on surface and subsurface temperature and salinity, and on precipitation and hence atmospheric heating and circulation (Collins *et al*. 2006). Large and Danabasoglu (2006) showed, in particular, with observed SSTs imposed along the BCS coast in an otherwise freely-evolving CCSM3 simulation, that there are significant improvements in precipitation in the western Indian Ocean, over the African continent and across the Equatorial Atlantic. Imposed SSTs along the HCS coast reduce precipitation in the so-called double Intertropical Convergence Zone region of the south tropical Pacific.

These errors often coincide with regions of importance to oceanic ecosystems and nearby human populations. In the IPCC-AR4 Working Group 1 Assessment Report, where the reliability of the models used to make projections of future climate change is assessed, Randall *et al*. (2007) discuss the many improvements and strengths of the current generation of coupled models of the physical climate system, but they also highlight a number of remaining significant model errors. Furthermore, they state "*The ultimate source of most such errors is that many important small-scale processes cannot be represented explicitly in models, and so must be included in approximate form as they interact with larger-scale features.*" Some of the reasons given for the deficiencies are limited computer power, data availability and scientific understanding. Conversely, regional models have shown significant skill in modeling coastal processes (*e.g*., Curchitser *et al.*, 2005, Powell *et al*., 2007, Combes *et al.*, 2009, Veneziani *et al.*, 2009a,b). This creates the opportunity, and perhaps necessity, to develop multi-scale numerical solution schemes that adapt the resolution in specific areas of interest, such as the CCS.

Figure 3.7.1 (top right panel) shows that the coastal winds in the latest CCSM4 with a 2° resolution (finite volume) atmosphere produce even larger SST biases than were apparent in CCSM3 (top left panel), despite many improvements to the physical model components. Improving the coastal winds by increasing the atmospheric resolution to 1°, however, significantly reduces the coastal SST biases (Fig. 3.7.1, bottom). The implication is that the further reductions in the SSTs required to eliminate the coastal biases under present day conditions will likely also need to come from improvements to the ocean physics and the upwelling of cold water in particular. These improvements must be realized before the regional biogeochemistry and ecosystem models can be expected to behave accurately because of the sensitivity to temperature and the critical importance of upwelled nutrients for biological processes.

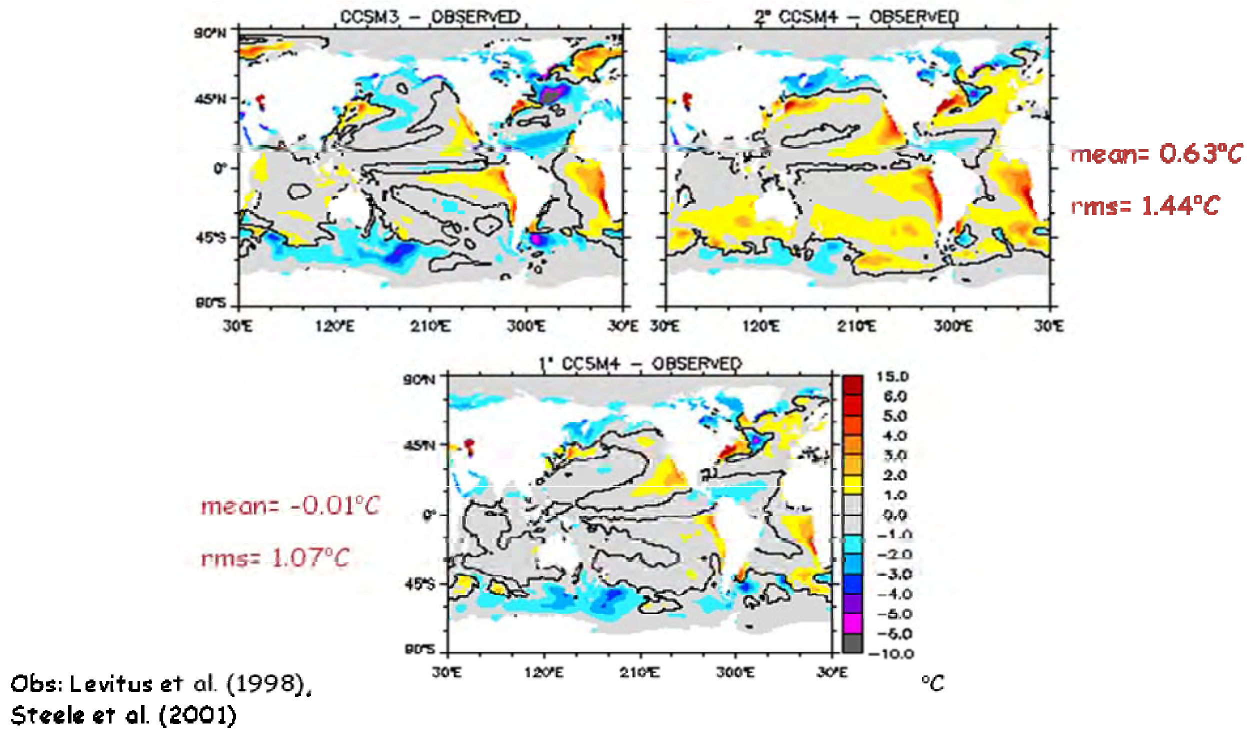

Fig. 3.7.1 Differences between model and present day observed sea surface temperature (SST) for the CCSM3 run with present day conditions (top left panel), for CCSM4 with a 2° atmosphere run with 1850s conditions (top right panel) and for CCSM4 with a 1° atmosphere run with 1850s conditions (bottom panel). Courtesy of G. Danabasoglu.

One approach to achieve high-resolution climate-scale simulations in a given domain is the nesting of a high-resolution limited-area grid within a lower resolution large-scale numerical domain (Ito *et al.*, 2010). With a nesting approach, information is downscaled from a coarse to a fine resolution region through an overlap in the domains. "Simple" downscaling using one-way flow of information works well when the forcing data are constrained by observations, such as in the case when using atmospheric reanalysis products (*e.g.*, Kalnay *et al.*, 1996). The high-resolution nest can explicitly resolve features missing from the large-scale model simulation, though it is still constrained through the boundaries by the large-scale climate patterns. However, when using freely-evolving coupled models, such as those used by IPCC to study past and future climate, the mean resulting climate is unconstrained by observational data. Therefore, a given atmospheric model can be expected to respond differently to an alternative (*e.g.*, high-resolution) ocean in the coupled system. The challenge is then to not only downscale information to the local scales, but also to understand how regional variability affects the global climate.

In order to address the above issues, we developed a new multi-scale ocean as part of the U.S. NCAR-CCSM. The new composite ocean consists of the global Parallel Ocean Program (POP) and the Regional Ocean Modeling System (ROMS). The new composite ocean is connected to the rest of the CCSM climate model through a modified flux coupler (Fig. 3.7.2).

Results from the Multi-scale Coupled Model

In order to test and demonstrate the capabilities of the multi-scale climate model, we have been carrying out a series of simulations where the Northeast Pacific upwelling region is solved using a high-resolution (10 km) ocean within a global (1°) model. The atmosphere is on a spectral grid (~2°), sea ice is solved on the ocean grid and the land surface model on the atmospheric grid. The CCSM is initialized from a spun-up climatology and time-stepped for 150 years. This simulation is then compared to a control run without the high-resolution ocean. Figure 3.7.3 is a close-up look at the Northeast Pacific showing the anomaly in the SST in a coupled climate simulation between a case with the composite ocean and the control, for all the available months of August (upwelling season). Superimposed are wind vector anomalies. What is seen is that the new multi-scale ocean is able to resolve the upwelling that is mostly missing from the global simulations, and this has a significant effect on the regional wind patterns.

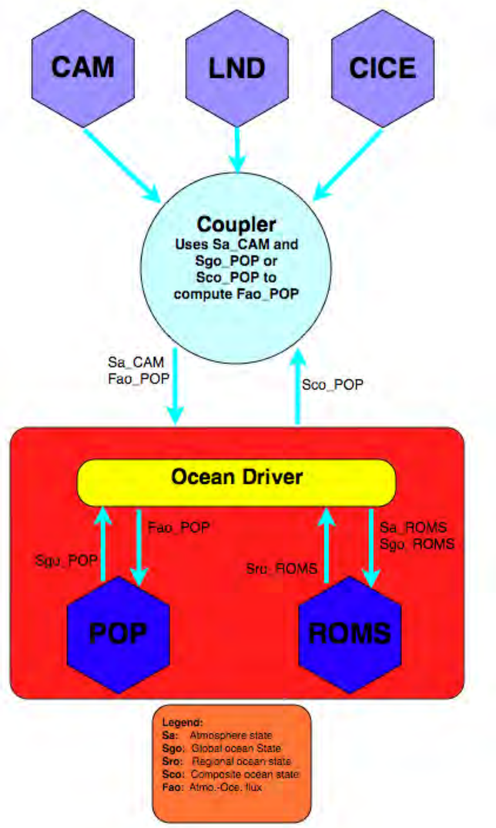

Fig. 3.7.2 Schematic of the multi-scale CCSM. The original ocean module (POP) has been replaced by a composite POP/ROMS module that is controlled by a newly designed ocean driver. The ocean driver passes fluxes and state variables to the respective oceans, controls the communications between the global and regional oceans (boundary conditions) and also assembles the output of the two oceans (*e.g.*, SSTs) that are passed to the coupler for the computation of the fluxes to the atmosphere (CAM), land (LND/CLM) and sea ice (CICE/CSIM) modules.

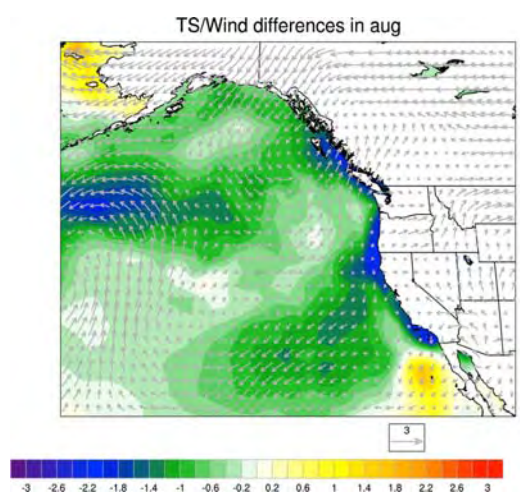

Fig. 3.7.3 SST anomolies using the composite ocean relative to a control run averaged over all available Augusts for the Northeast Pacific. Superimposed are the corresponding wind anomolies. Note the cooler upwelling SSTs and modified wind patterns.

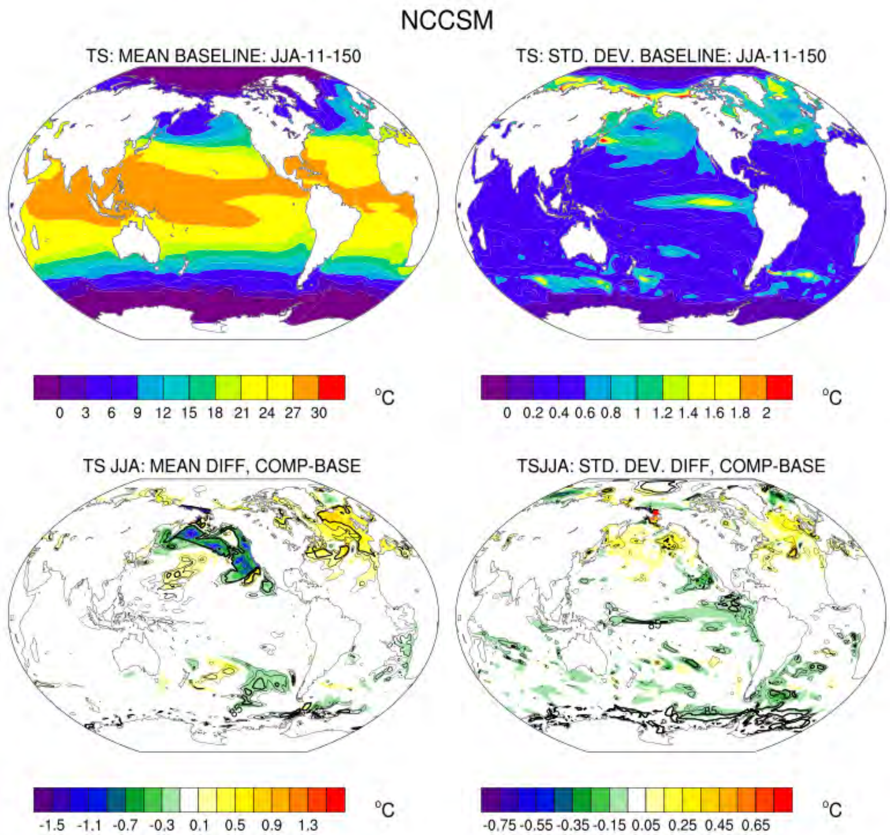

Fig. 3.7.4 Mean and standard deviation for the summer months of the control (top) and composite (bottom) simulations. Thick black lines in the composite simulation indicate 95% confidence level using the T- and F-test for the mean and deviation, respectively. Note both the local and remote effects caused by the perturbation that results from resolving the upwelling signal in the northeast Pacific region.

Figure 3.7.4 shows the SST and standard deviation for summer months (June–August) of the control simulation and the corresponding anomalies with the composite model for the last 140 years of simulation. The temperature anomaly plot shows the local cooling effect that results from resolving the upwelling in the Northeast Pacific and also remote effects in the Atlantic Ocean. Significant and robust effects are also seen in other variables such as tropical precipitation and sea level pressure.

Summary

A new multi-scale capability was developed by merging a global and a regional ocean model within a global climate model. The goal was to address some of the biases exhibited by low-resolution global models in regions with implications to marine ecosystems. Long integrations show that this configuration is able to address some of these regional biases. Furthermore, by preserving the feedbacks between the regional and global climate models, we are able to study upscaling effects that arise from the regionally introduced perturbations. In the case presented here, we see the effect as far afield as the North Atlantic Ocean. Further studies are in progress to study the effects of resolving other major upwelling regions, as well a new study in a western boundary current region where global models also show SST biases. Future plans include adding a biogeochemistry model to this configuration in order to study the role of upwelling regions in global CO_2 cycles.

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3.8 Pacific climate variability in IPCC coupled climate models

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Modes of North Pacific and Tropical Pacific Coupled Climate Variability

Interannual and decadal-scale variability of the North Pacific Ocean and the overlying atmosphere significantly impact the weather and climate of North America and Eurasia and drive important state transitions observed in marine ecosystems across the Pacific Ocean (see a recent review by Alexander (2010) and references therein). The Pacific Decadal Oscillation (PDO) (*e.g.*, Mantua *et al.*, 1997) emerges as the leading mode of North Pacific sea surface temperature (SST) anomalies (SSTa). The PDO to first order is the forced response of the North Pacific ocean surface to variability in the Aleutian Low (AL), the leading mode of North Pacific sea level pressure (SLP) anomalies (SLPa). Temporal modulations in the PDO are linked to several important biological and ecosystem variables in the ocean (*e.g.*, Hare and Mantua, 2000) and the location of the Kuroshio current in the western North Pacific Ocean (*e.g.*, Qiu *et al.*, 2007).

The second leading mode of oceanic variability in the North Pacific is the North Pacific Gyre Oscillation (NPGO), formally defined as the second leading mode of Northeast Pacific SSHa and drives prominent low-frequency changes in physical and biological variables across the Pacific (*e.g.*, SSTs, nutrients, chlorophyll-*a*) (*e.g.*, Di Lorenzo *et al.* 2008, 2009). Recent work by Chhak *et al.* (2009) and Di Lorenzo *et al.* (2010) demonstrates that the NPGO is the oceanic response to atmospheric forcing associated with the North Pacific Oscillation (NPO), defined as the second leading mode of North Pacific SLPa (*e.g.*, Walker and Bliss, 1932; Rogers, 1981; Linkin and Nigam, 2008). The NPGO also has relations with the strength of the Kuroshio current in the western North Pacific Ocean (*e.g.*, Ceballos *et al.*, 2009).

While the dynamics of these coupled ocean–atmosphere modes – namely the AL/PDO and NPO/NPGO – include elements independent of the tropics (*e.g.*, Latif and Barnett, 1994; Barnett *et al.*, 1999 and others), several studies have shown that significant fractions of the interannual (2–7 year band) and decadal (>7 years) variability of both the AL/PDO and the NPO/NPGO are intimately tied to variations in the tropical Pacific (*e.g.*, Alexander *et al.*, 2002; Newman *et al.*, 2003; Deser *et al.*, 2004, 2006; Di Lorenzo *et al.*, 2010). The tropical Pacific variations are directly related to changes in the El Niño–Southern Oscillation (ENSO) phenomenon and a recently recognized "flavor" of ENSO known as El Niño-Modoki (*e.g.*, Ashok *et al.*, 2007) or Central Pacific Warming (CPW) (*e.g.*, Kao *et al.*, 2009) which concentrates the maximum SSTa in the central tropical Pacific, not the far eastern tropical Pacific Ocean, as during canonical ENSO events.

Figure 3.8.1 summarizes the connections between large-scale modes of variability in the extratropical North Pacific and tropical Pacific. The diagram consists of two "wheels" which represent the leading (red wheel) and secondary (blue wheel) modes of variability in the tropical and North Pacific basins. The red wheel illustrates that canonical ENSO events in the tropical Pacific connect to variability in the AL in the North Pacific, which is then integrated by the underlying ocean to form a substantial portion of the PDO signature. The blue wheel illustrates that CPW events are statistically and dynamically linked to variations in the NPO (*e.g.*, Di Lorenzo *et al.*, 2010), which is then integrated to form the NPGO pattern. An additional element of interest in Figure 3.8.1 is the dynamical connection from the extratropical North Pacific to the tropical Pacific in the blue wheel. This connection consists of the seasonal footprinting mechanism (SFM) (*e.g.*, Vimont *et al.*, 2001, 2003) whereby boreal wintertime variability in the NPO drives warm SSTa in the North Pacific that propagate into the central tropical Pacific by the end of spring/summer and initiates an ENSO-like response in the tropical Pacific. If the response is a CPW-type event, a positive feedback loop occurs (Fig. 3.8.1, blue wheel). This feedback may provide a longer year-to-year persistence of CPWs.

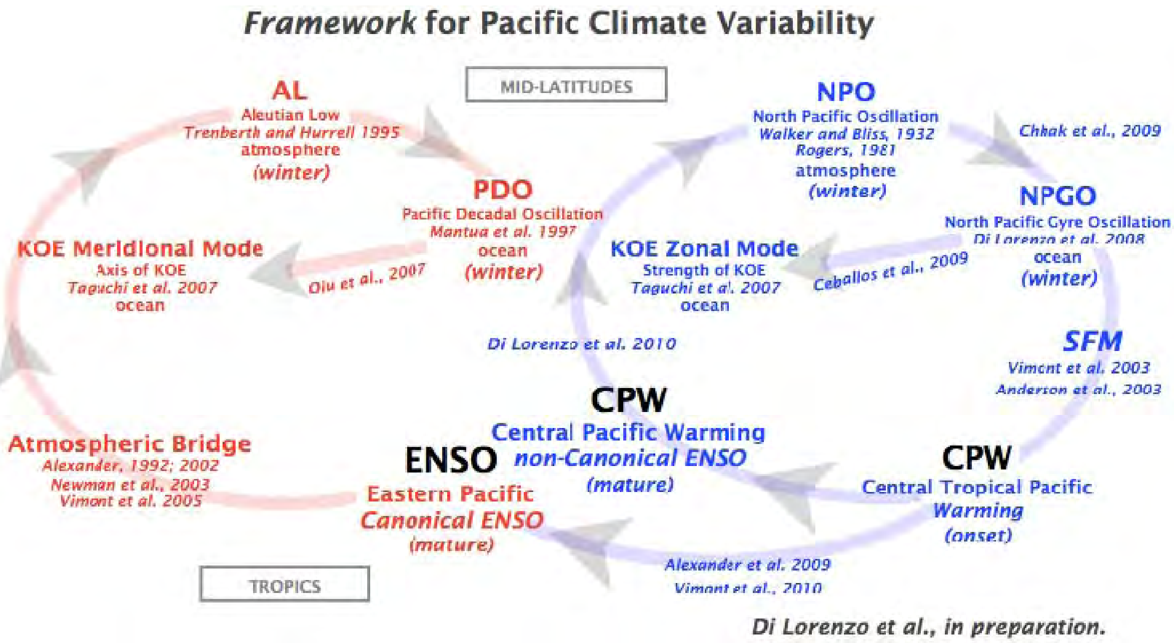

Fig. 3.8.1 Schematic of a proposed framework of Pacific climate variability showing the links between the ocean and atmospheric modes of low-frequency variability in the tropical and North Pacific.

Pacific Climate Variability in IPCC Coupled Climate Models

Figure 3.8.1 offers a dynamical framework that can be readily tested in state-of-the-art coupled climate models to see if the models are able to capture the links between the tropical and North Pacific modes of climate variability. Such connections are critical for testing as the fidelity of the future climate change offered by the models are directly related to the way they capture these Pacific dynamical connections. Furtado *et al.* (2011) provide a thorough examination of the major modes of North Pacific and tropical Pacific variability of the Coupled Model Intercomparison Projects phase 3 (CMIP3) models used to write the Inter-governmental Panel on Climate Change 4th Assessment Report (IPCC AR4). The authors focus on the 20th century hindcast simulations for evaluation (20C3M scenario) and quantitatively assess how well the models recover the leading modes of North Pacific climate variability in space and time, including their connections to the tropical Pacific.

The findings illustrate that, in general, the models perform poorly in reproducing the inherent frequencies of the AL/PDO and the NPO/NPGO modes as well as the connections between the tropics and extratropics. Figure 3.8.2 shows the spatial correlation between the leading modes of variability and covariability of North Pacific SLP and SST in the models *versus* observations for the 20th century. For the most part, the highest spatial correlations are for the leading modes of atmospheric patterns, not the ocean. This result suggests that the oceanic components of the coupled models fail to capture significant aspects of the PDO and especially the NPGO. Secondly, for the modes of covariability between North Pacific SST and SLP (*i.e.*, combined EOFs; cEOFs), cEOF-2, which represents the NPO/NPGO mode, has less reproducibility in the models than the AL/PDO pattern. This further suggests that there is a disconnect between the response of the North Pacific Ocean to the NPO forcing pattern within several of the models.

For implications on future climate change, the models show no consensus on projected future changes in the frequency of either the PDO or NPGO. No significant differences are anticipated in the spatial pattern or the frequency of either the PDO or the NPGO. This lack of a consensus in changes in either mode also affects confidence in projected changes in the overlying atmospheric circulation, including the projected changes in storm tracks and atmospheric tele-connection patterns (*e.g.*, Bengtsson *et al.*, 2006; Ulbrich *et al.*, 2008). Since the wind stress curl induced by the AL and NPO are drivers to the leading modes of North Pacific SSTa, we would expect that changes in their characteristics would change the dominant SSTa patterns, but the models do not illustrate such a change, suggesting that the dynamical coupling between the extratropical atmosphere and ocean needs to be addressed further.

The IPCC models are also deficient in replicating connections between the tropical Pacific and North Pacific in the models. Figures 3.8.3 and 3.8.4 show the first two modes of covariability between tropical and extratropical Pacific SLP and SST for the observations (Fig. 3.8.3) and the models (Fig. 3.8.4). Figure 3.8.3a and b clearly shows the canonical ENSO/PDO/AL connection in the first combined EOF in the observations, while Figure 3.8.3c and d demonstrates the relationship between the NPO and the CPW phenomenon. The regression patterns associated with the ENSO/PDO/AL and CPW/NPO patterns are statistically significant and support the dynamical framework laid out in the introduction. However, when the same combined EOFs are computed for the ensemble-mean of the 24 CMIP3 models, the relationships between the extratropical North Pacific and tropical Pacific nearly vanish for both leading modes. Figure 3.8.4 shows the combined EOFs of North Pacific and tropical Pacific wintertime SLPa/SSTa. For the first leading covariability mode (Fig. 3.8.4a and b), the models fail to capture a significant relationship with variability of the AL in the North Pacific (Fig. 3.8.4a) and almost no sign of the PDO-like response in the extratropical North Pacific, as shown in observations (compare Fig. 3.8.4b with Fig. 3.8.3b). For the CPW/NPO/NPGO mode in the models (Fig. 3.8.4c and d), the North Pacific atmospheric response does not resemble the classical NPO signature, with instead, an insignificant broad region of low pressure encompassing the North Pacific (Fig. 3.8.4c). The ensemble-mean SSTa regression pattern (Fig. 3.8.4d) shows the core of tropical Pacific warming displaced into the Warm Pool region. Moreover, in the North Pacific, the pattern better resembles the PDO pattern than that seen in the first covariability pattern (Fig. 3.8.4b and d). Though insignificant in the ensemble-mean, this difference suggests that variability associated with the PDO may have important connections with the *second* leading mode of tropical Pacific SSTa in many of the models, contrary to what is observed. Such findings are consistent with other previous studies with the CMIP3 models (*e.g.*, Newman, 2007).

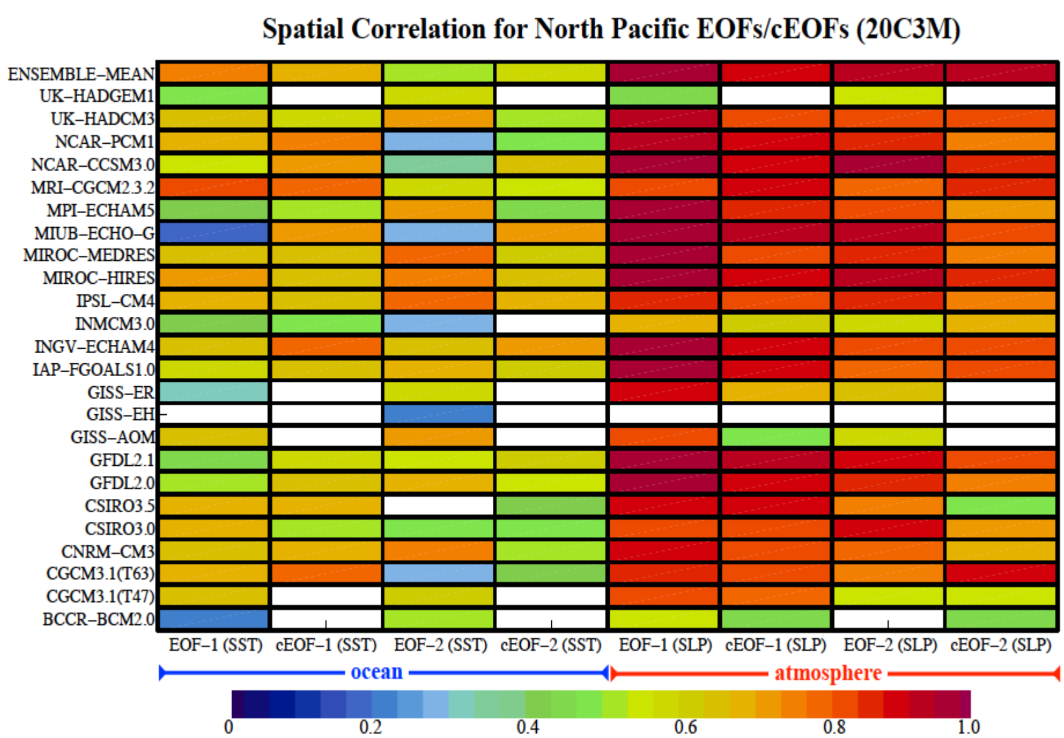

Fig. 3.8.2 Spatial correlation of leading modes of variability and covariability in the North Pacific atmosphere and ocean for SLP and SST fields. EOF-1 and EOF-2 of the ocean (atmosphere) refer to the PDO and NPGO (AL and NPO) modes. The cEOF modes refer to coupled EOFs of North Pacific SLP and SST. cEOF-1 (cEOF-2) refers to the AL/PDO (NPO/NPGO) mode. Only spatial correlations that are significant at the $p < 0.05$ level are shaded (adapted from Furtado *et al*., 2011).

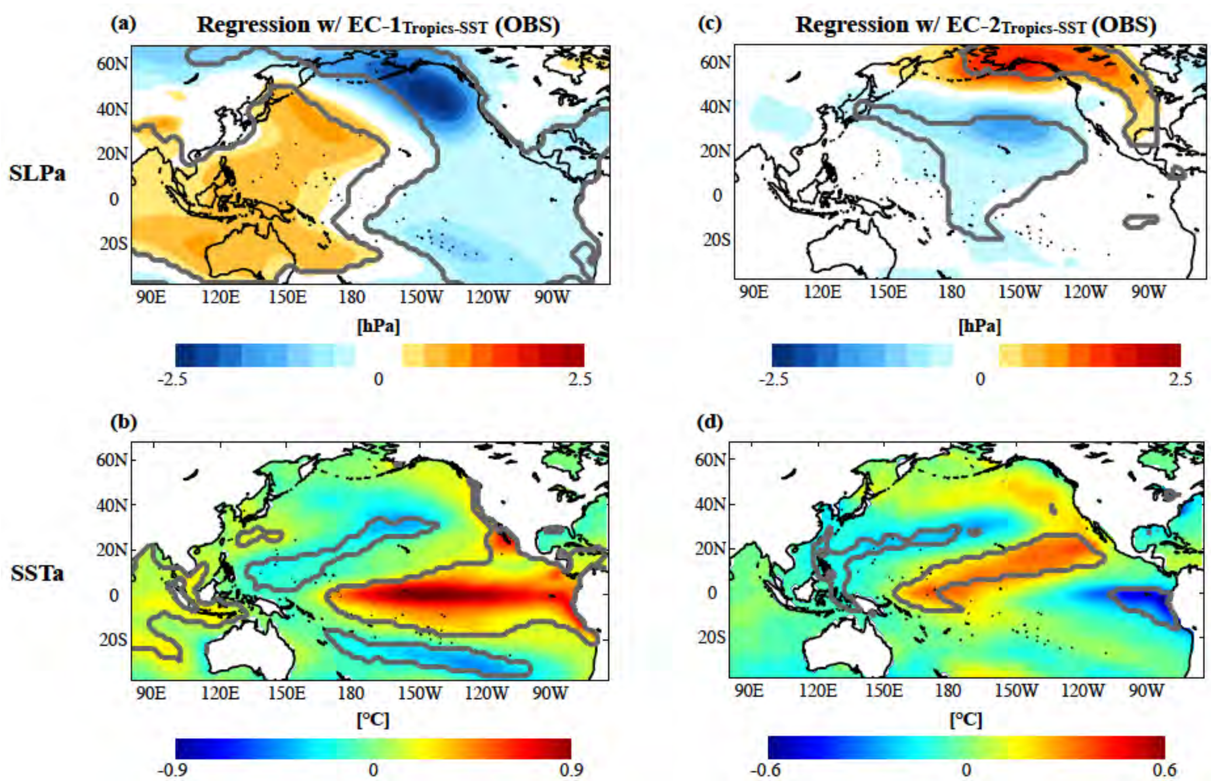

Fig. 3.8.3 Leading two modes of covariability between SLP and SST in the tropical and North Pacific in the observations. (a) The regression of observed wintertime NCEP/NCAR SLP (hPa) on the standardized first expansion coefficient time series (*i.e.*, EC-1) of observed tropical–North Pacific SLPa and SSTa. (b) As in (a) but for NOAA ER SSTa (°C). (c) As in (a) but regressed onto the standardized second expansion coefficient time series (EC-2) of tropical–North Pacific SLPa and SSTa. (d) As in (c) but for SSTa. The gray contour in all plots shows where the correlation values exceed the 95% significance level (adapted from Furtado *et al.*, 2011).

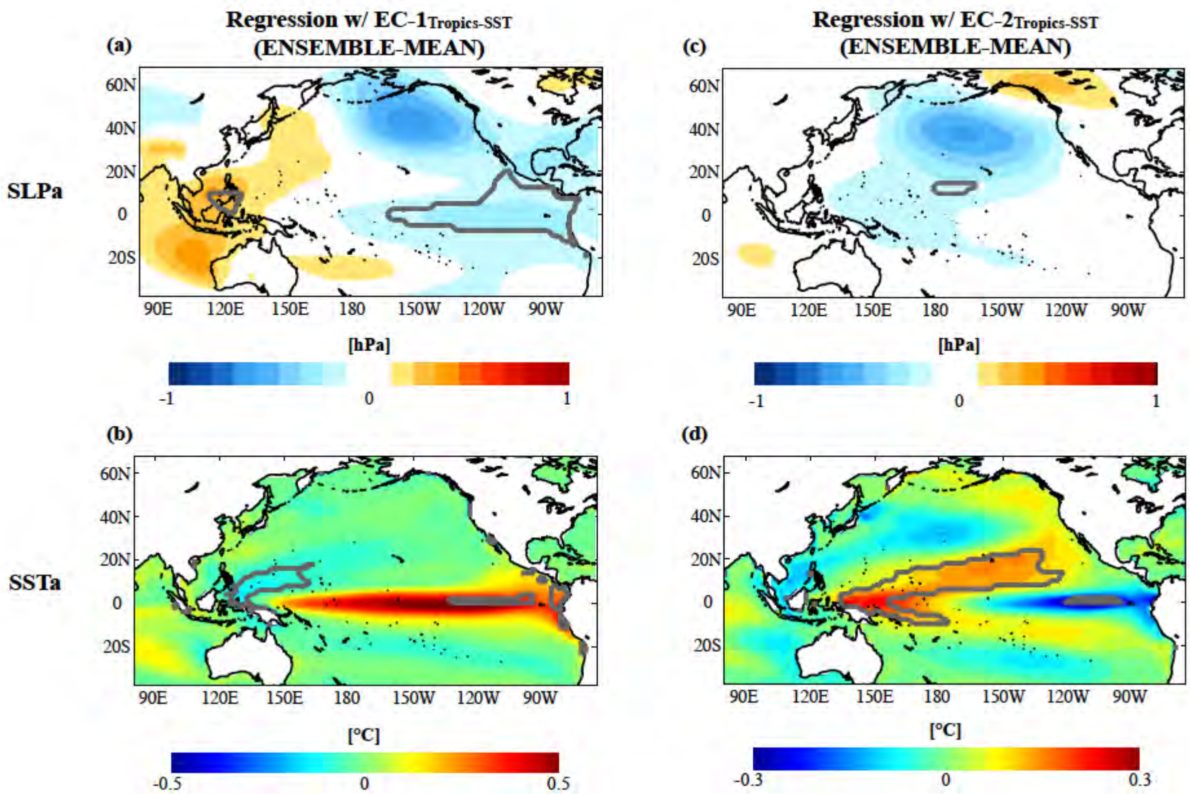

Fig. 3.8.4 Leading two modes of covariability between SLP and SST in the tropical and North Pacific in the CMIP3 models. (a) Ensemble-mean regression pattern (all 24 CMIP3 models) of wintertime SLPa (hPa) on the standardized first expansion coefficient time series (EC-1) of tropical–North Pacific SLPa and SSTa covariability. (b) As in (a) but for SSTa (°C). (c) As in (a) but regressed onto the standardized second expansion coefficient time series (EC-2) of tropical–North Pacific SLPa and SSTa. (d) As in (c) but for SSTa. The gray contour in all plots shows where the correlation values exceed the 95% significance level. Note that the scales in Figure 3.8.4 are smaller than those in Figure 3.8.3 (adapted from Furtado *et al.*, 2011).

Projected Changes in the Central Tropical Pacific and Impacts on North Pacific Climate

The ability of the coupled climate models in simulating tropical Pacific–North Pacific modes of climate variability is questionable based on the results of Furtado *et al.* (2011) and other similar studies. Yet, of late, the climate community has focused on apparent changes in ENSO frequency in the latter half of the 20th century and early 21st century, particularly on the apparent increase in CPW-type events in the SST record (*e.g.*, Ashok *et al*., 2007; Kim *et al*., 2009). Whether this increase in CPW events is simply because of the short length of records or is due to some low-frequency change in the tropical Pacific climate system remains to be seen. However, there are suggestions that CPW events will continue to increase in frequency and magnitude under global climate change (Yeh *et al.*, 2009), meaning that understanding the fundamental dynamics of the phenomenon and its relation to the rest of the North Pacific is important to investigate. This venture is especially important for verifying the proposed feedback loop between the CPW and the NPGO presented in Figure 3.8.1.

Di Lorenzo *et al.* (2010) investigated the links between the CPW phenomenon and its connection to the NPGO, particularly since the two phenomena share a similar SSTa footprint in the tropical Pacific Ocean. Using an ensemble of runs from a simple atmospheric model forced only with tropical Pacific SSTa (12°S–12°N), the authors demonstrated that central tropical Pacific SSTa force changes in the extratropical North Pacific, particularly the subtropical SLP field near Hawaii / the southern node of the NPO. The SLP response then forces the underlying ocean and generates the decadal-scale signature of the NPGO. Figure 3.8.5 recaps the main results from Di Lorenzo *et al.* (2010). Figure 3.8.5a–d

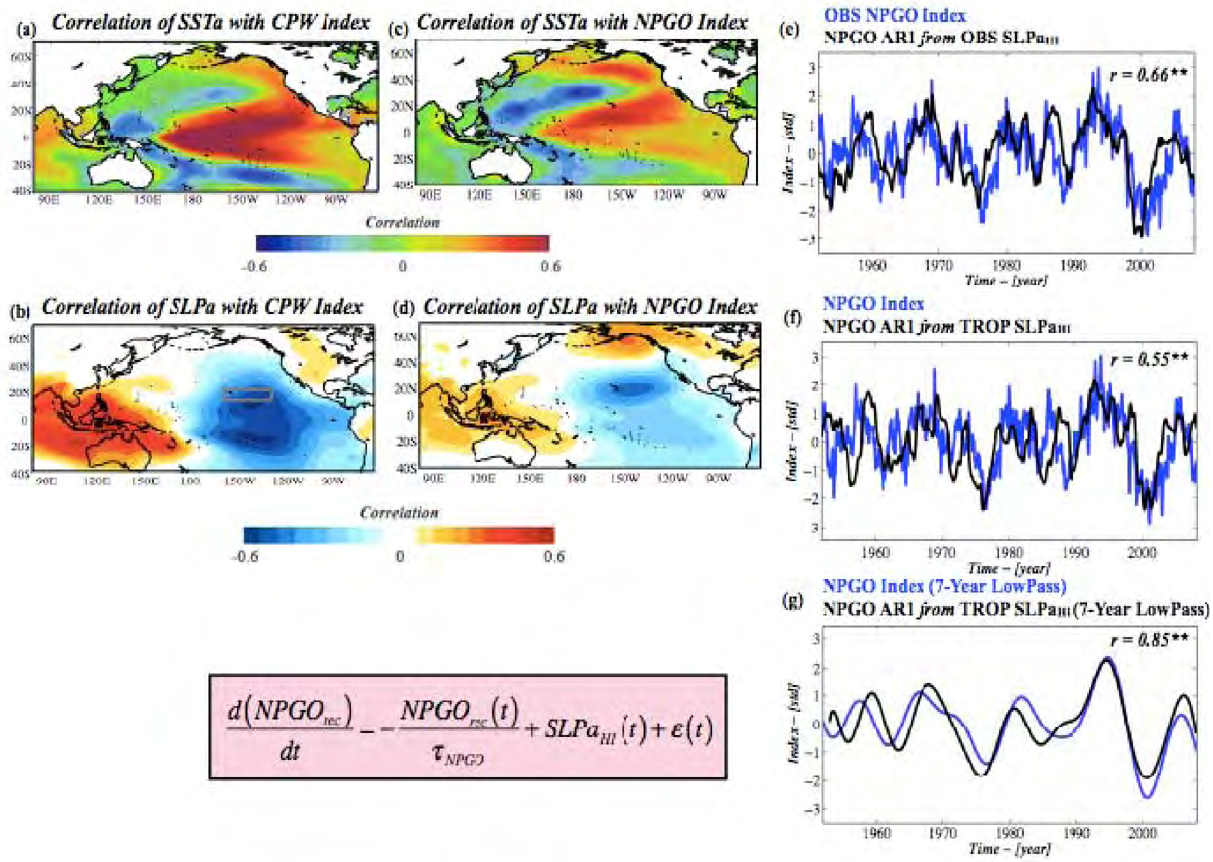

Fig. 3.8.5 Connecting the CPW phenomenon to the NPGO. (a) The contemporaneous correlation between the CPW index (defined as the second principal component of tropical Pacific SSTa) and NOAA ER SSTa. (b) As in (a) but correlation with NCEP/NCAR SLPa. Gray box defines the region used to compute the SLPa Hawaii index. (c) As in (a) but correlation with the NPGO index. (d) As in (b) but for the NPGO index. (e) The NPGO index (blue) and the reconstructed NPGO index (black) using an AR-1 model forced by the SLPa Hawaii index (AR-1 model shown in pink box). Correlation between the NPGO index and the reconstructed is $r = 0.66$, ($p < 0.01$). (f) As in (e) but the forcing for the AR-1 model reconstruction (black) in the ensemble-mean SLPa Hawaii index from the AGCM, which represents deterministic variability driven by the central tropical Pacific. The correlation between the observed and model reconstructed NPGO index is 0.55 ($p < 0.01$). (g) As in (f) but both indices filtered with a 7-year lowpass filter. The correlation between the two low-passed indices is $r = 0.85$ ($p < 0.01$), (adapted from Di Lorenzo *et al.*, 2010).

establishes the statistical relationship between the CPW and the NPGO. Note that both phenomena share common areas of correlation in the central tropical Pacific in SSTa (Fig. 3.8.5a and c) and also in SLPa, especially in the subtropical North Pacific near the Hawaiian Islands (Fig. 3.8.5b and d). The link between the central tropical Pacific SSTa and the NPGO variability is made apparent in the AR-1 model reconstructions presented in Figure 3.8.5e–g. Figure 3.8.5e establishes from observations that, indeed, the SLPa Hawaii index significantly captures nearly 44% of the variability in the NPGO index. When using the ensemble-mean from the model, nearly 30% is recovered in the model, which is statistically significant but, more importantly, remarkable for the simple model experiments performed. Finally, to show that some decadal-scale changes in the North Pacific are driven by the CPW phenomenon, the 7-year low-passed NPGO and model-reconstructed NPGO indices show excellent agreement ($r = 0.85$; $p < 0.01$).

Taken together, these results suggest that the low-frequency nature of the NPGO, which controls climate and ecosystem variations in the North Pacific, originates from variability associated with the CPW phenomenon. Such a result parallels previous studies that have connected canonical ENSO variability with variability in the PDO (*e.g.*, Alexander *et al.*, 2002; Newman *et al.*, 2003; Vimont, 2005). Given the uncertainties in tropical Pacific climate in the future and the inability of many coupled climate models to agree on a change or agree on governing dynamics in the extratropical–tropical Pacific climate system, there exists large uncertainties on the future state of Pacific decadal climate variability. If projections of increased CPW frequency and magnitude are accurate (*e.g.*, Yeh *et al*., 2009), then the results in Figure 3.8.5 illustrate that we might expect an increased variance in the NPGO phenomenon as well, which would alter the background state of the North Pacific and its ecosystems.

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3.9 Examples of using Global Climate Models for regional climate projections

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Introduction

Comprehensive Atmosphere–Ocean General Circulation Models (AOGCMs) comprise the major objective tool that scientists use to account for the complex interaction of processes that determine future climate change. Such model projections formed the basis of the Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC AR4, Solomon *et al.*, 2007) and are now archived as part of the Coupled Model Intercomparison Project phase 3 (CMIP3; Meehl *et al.*, 2007). While global climate models provide credible quantitative estimates of future climate at continental scales and above (Solomon *et al.*, 2007), the projections at regional scales from these climate models have a larger spread and uncertainty. Yet climate projections at regional scales are in increased demand from governments, management agencies and other stakeholders. Regional projections from these models are also being used by management agencies to assess and plan for future ecological and societal impacts. While it is clear that the CMIP3 models are better than the earlier models used for the 3rd Assessment Report (Randall *et al*., 2007; Reichler and Kim, 2008), there remains a general question: how reliable are these model projections at regional scales and what is the limit of their utility? There are, in fact, considerable differences in the models' ability to hindcast regional climate variability based on location, variable of interest, and metrics – *e.g.*, means, variance, trends – with no convergence toward a single subset of preferred models. Thus, the question of model reliability has no simple quantitative answer; there is no one best model (Räisänen 2007; Gleckler *et al*., 2008; Reifen and Toumi, 2009).

In this report, we assess 24 models that submitted their simulation results to the Program for Climate Model Diagnosis and Intercomparison (PCMDI; http://www-pcmdi.llnl.gov/ipcc/info_for_analysts.php). Model names, the contributing country and their resolutions for the atmosphere and ocean, as well as the number of ensemble runs submitted, are summarized in Table 3.9.1. Although there is emerging evidence of the utility of some regional climate model projections, users should strive to evaluate uncertainties in the multiple model simulations. We present a set of considerations to guide regional applications of CMIP3, that is, to extract the future climate projections from current available models at regional scales, with careful model culling for each variable of our interest. Below, we present our results for two selected variables which are important to the Bering Sea marine ecosystem.

There are three main sources of uncertainty in the use of AOGCMs for climate projections: large natural variations (both forced and unforced), the range in emissions scenarios, and across-model differences (Hawkins and Sutton, 2009). First, it is known that if climate models are run several times with slightly different initial conditions, the trajectory of day-to-day and, indeed, year-to-year evolution, will have different timing of events even though the underlying statistical-spectral character of the model climate tends to be similar for each run. This variability is a feature of the real climate system, and users of climate projections must recognize its importance. Natural variability is a source of ambiguity in the comparison of models with each other and with observational data. This uncertainty can affect decadal, or even longer means, so it is highly relevant to the use of model-derived climate projections.

A second source of uncertainty arises from the range in plausible emissions scenarios. Emissions scenarios have been developed based on assumptions of future development of technology and population (Nakicenovic *et al*., 2000). So the greenhouse gases and aerosol concentrations are derived based on assumptions, which are then used to drive the AOGCMs in the form of external forcing specified in the CMIP3 models, as summarized in the IPCC AR4. Because of the residence time of carbon in the atmosphere and the thermal inertia of the climate system, climate projections are often relatively insensitive to the precise details of which future emissions scenarios are used over the next few decades, as the impacts of the scenarios are rather similar before mid-21st century (Hawkins and Sutton, 2009). For the second half of the 21st century, however, and especially by 2100, the choice of the emission scenario becomes a major source of uncertainty of climate projections and dominates over natural variability, at least for temperature, and model-to-model differences (Solomon *et al*., 2007).

The third source of uncertainty is termed across-model uncertainty, which can be separated into parameterization uncertainty and structural uncertainty (Knutti, 2008). Due to the coarse resolution of global climate models, and due to computational restrain, sub-grid scale processes must be parameterized, requiring specification of functional relationships and tuning of attendant coefficients. Different numerical approximations of the model equations, spatial resolution, and other model development factors introduce structural uncertainty between different models.

Model uncertainty can be addressed, in part, through consideration of multi-model ensemble means. Below, through a few examples, we show how the ensemble mean can be constructed for two variables important to the ecosystem components of the Bering Sea. We used a two-step model culling strategy in which model variables are assessed in a large-scale content first, and then further evaluated on the regional scale, as illustrated by Figure 3.9.1.

North Pacific Sea Surface Temperature

Major changes in species distribution and abundance in North Pacific marine ecosystems are often correlated with climatic shifts in the 20th century, including halibut in the Gulf of Alaska, sardine near Japan and various species along the Oregon/ California coast (Peterson and Schwing 2003; Zhang *et al*. 2004; Chen and Hare, 2006). Over the North Pacific, the major mode of variability in the sea surface temperature (SST) field is the Pacific Decadal Oscillation (PDO) (Zhang *et al*., 1997; Mantua and Hare, 2002), which is identified by the leading mode of Empirical Orthogonal Function (EOF) of observed winter (November–March) North Pacific SST. The PDO has a general east/west dipole spatial structure (Fig. 3.9.2A) and decadal variability (dashed red line Fig. 3.9.2B). EOFs are an efficient way to display the relative importance of covariance in spatial fields, although they are a statistical pattern and not based directly on dynamics. When we applied EOF analysis to the model-simulated SST over the North Pacific, we found that 12 out of 23 models simulated the PDO close to the observed pattern, both spatially and temporally (Overland and Wang, 2007; Wang *et al*., 2010). These models are CCSM3, CGCM3.1 (T47), CGCM3.1 (T63), ECHAM5, ECHO-G, GFDL-CM2.0, GFDL-CM2.1, MIROC3.2 (hires), MIROC3.2 (medres), MRI, PCM1, and UKHadCM3. When an EOF analysis is applied to the SST of the 21st century model projections, the first EOF of SST variability from these models is a new, rather uniform, single-signed loading pattern (Fig. 3.9.2C) with a corresponding principal component (PC) time series showing an upward trend (solid blue line, Fig. 3.9.2B). Now, the second leading pattern of the 21st century SST variability (Fig. 3.9.2D) shows the spatial variability of the PDO dipole pattern, similar to the 20th century observed field (Fig. 3.9.2A). The spatial correlation between these two patterns is 0.82.

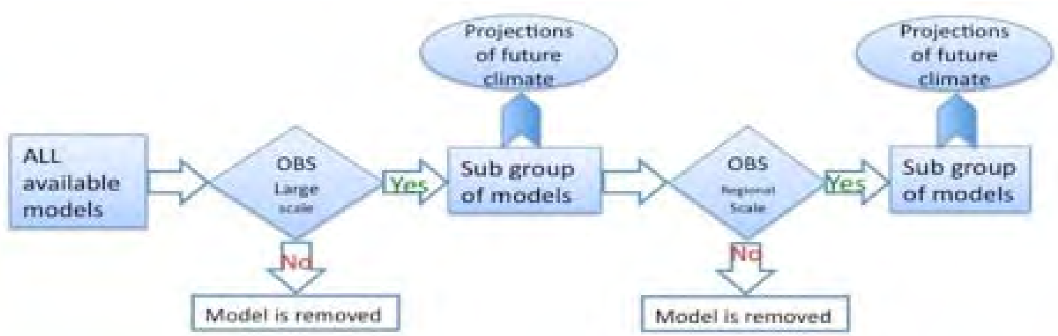

Fig. 3.9.1 Schematic plot of the model culling procedure for a given variable for selected region.

Table 3.9.1 List of coupled atmosphere–ocean models and available number of ensemble runs archived for selected variables (SAT, SST, and sea ice concentration) in 20c3m simulations.

	IPCC I.D.	Country	Atmosphere resolution	Ocean resolution	SAT	SST	Sea Ice
1	BCCR-BCM2.0	Norway	2.8° × 2.8°L31	(0.5-1.5°) × 1.5°L35	1	1	1
2	CCSM3	USA	1.4° × 1.4°L26	(0.3-1.0°) × 1.0°L40	8	2	7
3	CGCM3.1 (T47)	Canada	3.75° × 3.7°L31	1.9° × 1.9°L29	5	5	5
4	CGCM3.1 (T63)	Canada	2.8° × 2.8°L31	1.4° × 0.9°L29	1	1	1
5	CNRM-CM3	France	2.8° × 2.8°L45	2° × (0.5°-2°)L31	1	1	1
6	CSIRO-Mk3.0	Australia	1.875° × 1.865°L18	1.875° × 0.925° L31	3	3	3
7	CSIRO-Mk3.5	Australia	1.875° × 1.865°L18	1.875° × 0.925° L31	1	1	3
8	ECHAM5/ MPI-OM	Germany	1.875° × 1.865°L31	1.5° × 1.5°L40	4	3	3
9	FGOALS-g1.0 (IAP)	China	2.8° × 2.8°L26	1° × 1°xL30	3	3	3
10	GFDL-CM2.0	USA	2.5°x2.0° L24	1° × 1°L50	3	3	3
11	GFDL-CM2.1	USA	2.5° × 2.0° L24	1° × 1°L50	3	5	5
12	GISS-AOM	USA	4° × 3°L12	1.4° × 1.4°L43	2	2	2
13	GISS-EH	USA	5° × 4°L20	2° × 2° *cos(lat) L16	5	5	–
14	GISS-ER	USA	5° × 4°L13	5° × 4°L33	9	9	9
15	INGV-SGX	Italy	1.125° × 1.12°L19	1° × 1°L33	1	1	1
16	INM-CM3.0	Russia	5° × 4°L21	2°x2.5°L33	1	1	1
17	IPSL-CM4	France	3.75° × 2.5° L19	2° × 1°L31	1	1	1
18	MIROC3.2 (hires)	Japan	1.125° × 1.12° L56	0.28° × 0.188° L47	1	1	1
19	MIROC3.2 (medres)	Japan	2.8° × 2.8°L20	(0.5°-1.4°) × 1.4° L44	3	3	3
20	ECHO-G (MIUB)	Germany/Korea	3.75° × 3.7°L19	(0.5°-2.8°) × 2.8° L20	5	3	3
21	MRI-CAOGCM2.3.2	Japan	2.8° × 2.8° L30	(0.5°-2. 5°) × 2° L23	5	5	5
22	PCM	USA	2.8° × 2.8°L18	(0.5-0.7°) × 0.7° L32	4	3	2
23	UKMO-HadCM3	UK	3.75° × 2.5° L15	1.25° × 1.25° L20	2	2	2
24	UKMO-HadGEM1	UK	1.875° × 1.25°L16	(0.33-1.0°) × 1.0° L40	2	2	2
	Total Runs				74	66	67

Note: The number after letter “L” indicates the number of vertical levels in the model. If no archive is available for selected variable, then no number is given in the column.

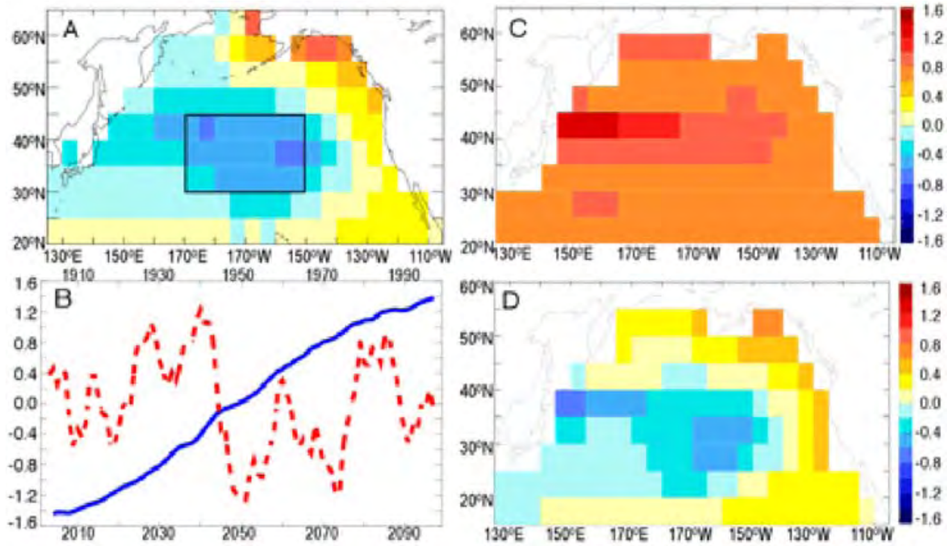

Fig. 3.9.2 (A) The first leading EOF pattern of the North Pacific winter (November–March) sea surface temperature (SST) anomalies for 1901–1999 based on Hadley Center SST analysis, *i.e.*, the PDO. (B) Principal component (PC) timeseries corresponding to the pattern in (A) for the 20th century (dashed line, time axis on top). (C) The first leading EOF pattern of winter SST for 2001–2099 period based on the ensemble mean of models. The corresponding model mean PC series is shown by the solid line in (B) (time axis on bottom). (D) The mean of the second leading EOFs for the 21st century model projections.

Arctic Sea Ice Extent

Even though climate models show that future temperature increases from anthropogenic forcing are amplified at high latitudes due to positive feedbacks involving snow, sea ice and ocean process, the Arctic is, in fact, changing even faster than anticipated from model projections summarized by the IPCC AR4 (Serreze and Francis, 2006; Serreze *et al*. 2007; Solomon *et al*., 2007; Stroeve *et al*., 2007). After the sharp decline in the sea ice coverage of summer 2007, we have seen a consecutive four years of least sea ice extent over the history of the satellite era (Fig. 3.9.3). This might be a reflection of the positive feedback in the Arctic climate system due to significant reduction of the sea ice.

Many projections from CMIP3 models show an increased rate of sea ice loss when sea ice extent is near the present 4.6 million km^2 mark compared to sea ice extents before 2000, which suggests increased impacts of ocean/ice feedback processes when the summer Arctic Ocean open water area increases. Applying observational constraints (mean and seasonal cycle) to model-simulated Northern Hemispheric sea ice extent for the 1980–1999 period, Wang and Overland (2009) identified 6 models (CCSM3, CNRM-CM3, ECHO-G, IPSL-CM4, MIROC3.2 (medres) and UKHadGEM1) that show reasonable fidelity to the observed sea ice extent in the 20th century. The selection process reduces the range of uncertainties in the future projections by these models as shown in Figure 3.9.4. It also shows that the models reproduced reasonable seasonal cycles relative to the observations, predicting faster sea ice decline (thick blue line in Fig. 3.9.4) than all model ensemble means (thick yellow line).

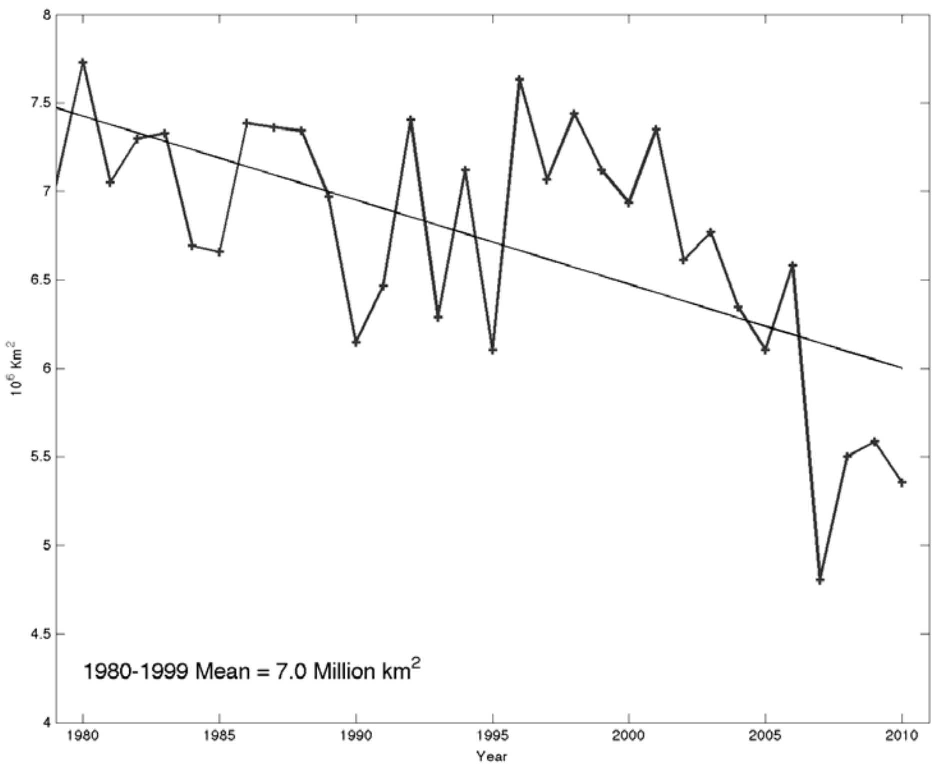

Fig. 3.9.3 Northern Hemisphere sea ice extent for September during the satellite era based on Hadley sea ice analysis. Data are available from http://www.metoffice.gov.uk/hadobs/hadisst/data/download.html.

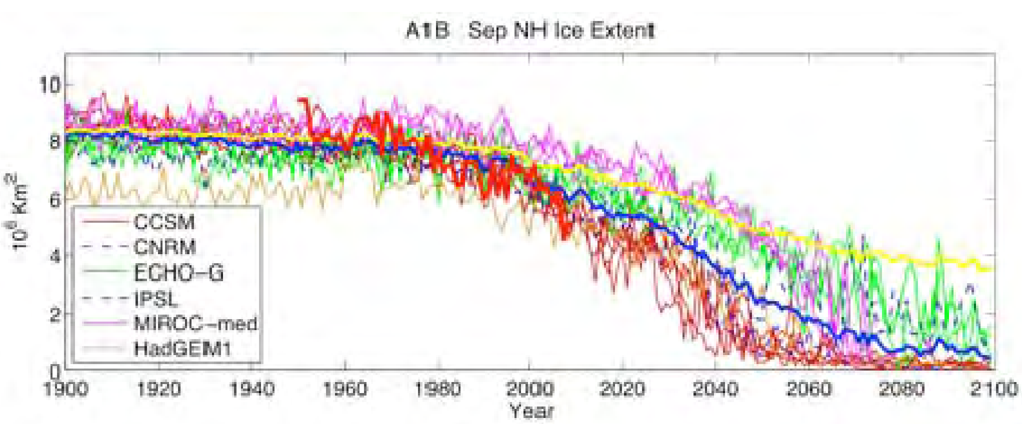

Fig. 3.9.4 Sea ice extent simulated by 6 models under the A1B emissions scenario. The thick blue line is the ensemble mean averaged over the 6 models, whereas the thick yellow line is the ensemble mean averaged over all 23 (excluding FGOALS) model runs. The thick red line is based on Hadley Sea ice analysis.

Projection of Bering Sea Future Climate

The Bering Sea, located in the north end of the Pacific Ocean, is connected to the Arctic Ocean through the Bering Strait. Its geographic location determines that its climate is influenced by the changes in the Arctic from the north and the Pacific from the south. Here, we take the SST and sea ice coverage as two examples to illustrate how the global climate models are being assessed and culled for the Bering Sea projection.

Sea surface temperature

Since the Bering Sea is seasonally covered by sea ice, sea ice simulation will have an impact on its SST status for the region. We start with 15 models identified by Wang and Overland (2009), and Wang *et al*. (2010), which simulated either the sea ice condition over the Arctic or the PDO feature in North Pacific well. We then further evaluate these models' performance at a regional scale over the Bering Sea for each variable independently before we select a subgroup of models to make projections for the future. Considering the significant difference of physical oceanic conditions resulting from the underlying bathymetry, we further divide the Bering Sea into the eastern Bering (54°–66°N, 165°E–175°W), and the western Bering (54°–66°N, 175°–155°W). Figure 3.9.5 shows the climatology of the SST with the annual mean removed over the eastern (Fig. 3.9.5a) and western (Fig. 3.9.5b) Bering Sea from 7 out of the 15 models (ECHAM5/MPI, GFDL-CM2.0, GFDL-CM2.1, IPSL-CM4, MIROC3.2 (medres), MRI-CAOGCM2.3.3, and UKHadGEM1) that simulated the seasonal cycle in reasonable agreement with observations. The seasonal cycle is well captured by these 7 models, and besides, all models have correctly placed maximum SST in August.

Projections of future SST for the eastern and western Bering Sea are shown in Figures 3.9.6 and 3.9.7. An apparent and similar upward linear trend in the SST field is seen over both sides of the Bering Sea. By the end of the 21st century, about a 3°C temperature increase is projected by the ensemble mean for each month.

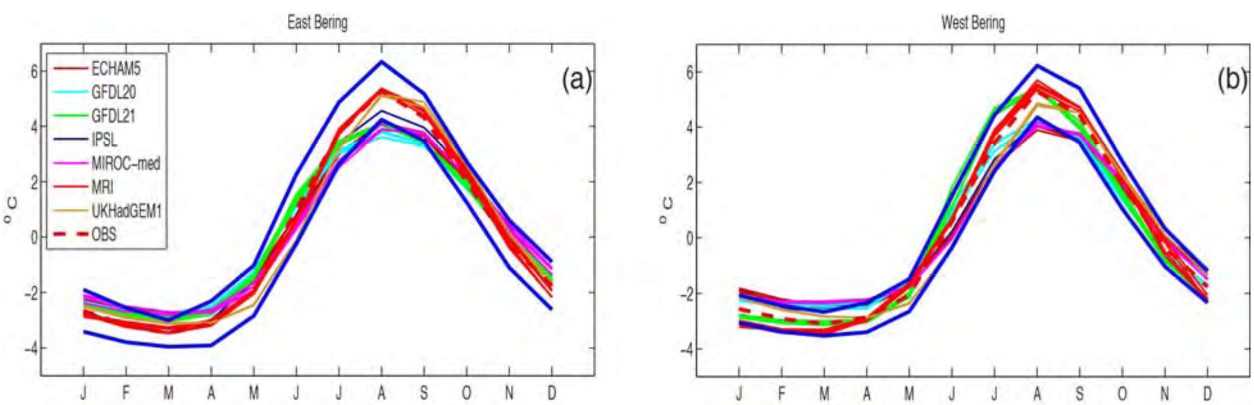

Fig. 3.9.5 Climatology of sea surface temperature (SST) averaged over (a) the eastern Bering Sea and (b) western Bering Sea for 1982–1999 based on seven models which passed both the PDO and sea ice test. The thick dashed red line is based on observation (HadSST), and the thick blue lines give the envelop for +/– two standard deviations.

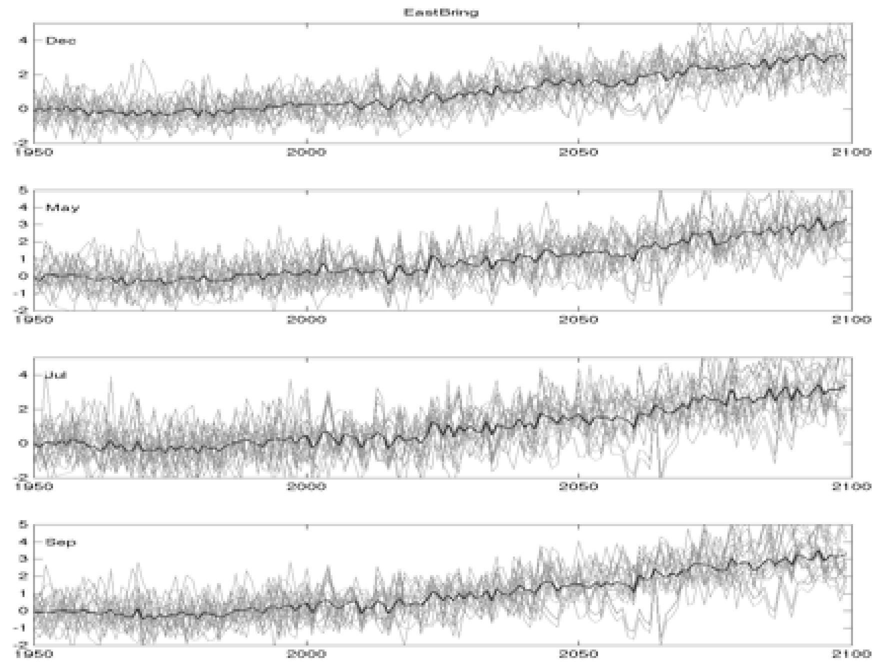

Fig. 3.9.6 Sea surface temperature (SST) anomalies relative to its climatology of the1980–99 period for selected months to represent each season based on 7 models which passed either the sea ice or PDO tests, and simulated the seasonal cycle of SST over the eastern Bering Sea in good agreement with observed values. Each grey line represents one realization from these 7 models and the thick black line shows the ensemble mean under A1B emissions scenario.

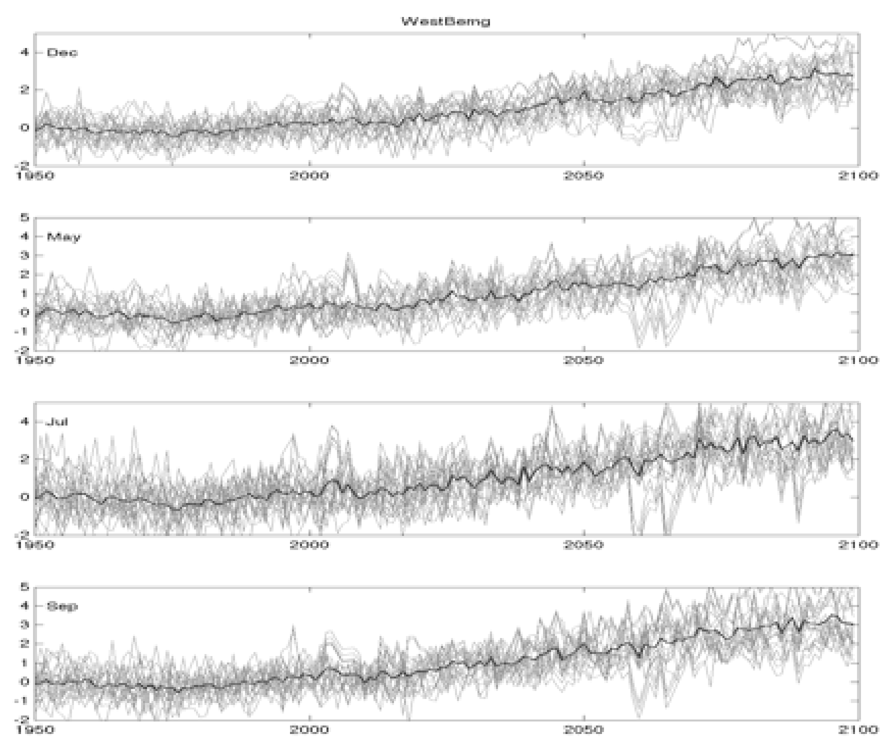

Fig. 3.9.7 Similar to Figure 3.9.6 but for SST over western Bering Sea. Each grey line represents one realization from these 7 models and the thick black line shows the ensemble mean under A1B emissions scenario.

Sea ice extent

As discussed in the introduction, sea ice plays an important role not only in the physical environment, but also provides habitat for marine mammals such as seals and polar bears. Starting with the 6 models identified by Wang and Overland (2009) that passed the performance criteria, we further evaluate these 6 models for their performance over the eastern Bering Sea and the western Bering Sea, independently. We found that 4 out of the 6 models perform reasonable well for the eastern Bering Sea (Fig. 3.9.8a), and only few runs from one model perform well in the western Bering Sea (Fig. 3.9.8b). This allows projections to be made from 4 models (CCSM3, CNRM-CM3, ECHO-G, and MIROC3.2 (medres)) for the eastern Bering Sea. Since only one model produced the climatology well in the western Bering Sea, at this point we do not have enough confidence to provide projections for the future sea ice extent for this region. This is because a single model could not provide enough runs to assess the uncertainty.

Figure 3.9.9 displays the projected sea ice extent from the models for selected months (December, February, April and June) over the eastern Bering Sea under both the A1B and A2 emissions scenarios. In late fall or early winter (December), there is sea ice cover over the eastern Bering Sea, even by the middle of the 21st century, yet the declining trend is visually obvious. The same is true for late winter (February) and spring (April). The grey lines from the models show that the interannual variability of the sea ice extent is large in these two months, compared with other time periods of the year. By the end of spring (June), sea ice is basically gone. This is true for the last few decades, and will be true in the future although occasionally there can be a year that sea ice still exists in part of the eastern Bering in June, but this is rare. The estimated downward trend is -2.1×10^3 km^2 /year for December, -3.0×10^3 km^2 for February, and -2.7×10^3 km^2 for April. There is no ice cover over the eastern Bering Sea during the summer and fall (July to November). The decline in sea ice extent is projected to occur faster in winter months in the first half of the 21st century than in the second half. For example, the linear decline trend is -3.9×10^3 km^2/year for 2000–2049, and is -0.5×10^3 km^2/year for 2050–2099. By 2050, the averaged sea ice extent would be 28% of present day value (relative to the 1980–1999 period mean), whereas the spring sea ice extent (average of March to May) would be at 58% of the present value. By 2075 the spring sea ice extent would be reduced to 37% of the present day value, and the autumn would be at only 12% of the present day value (figures not shown).

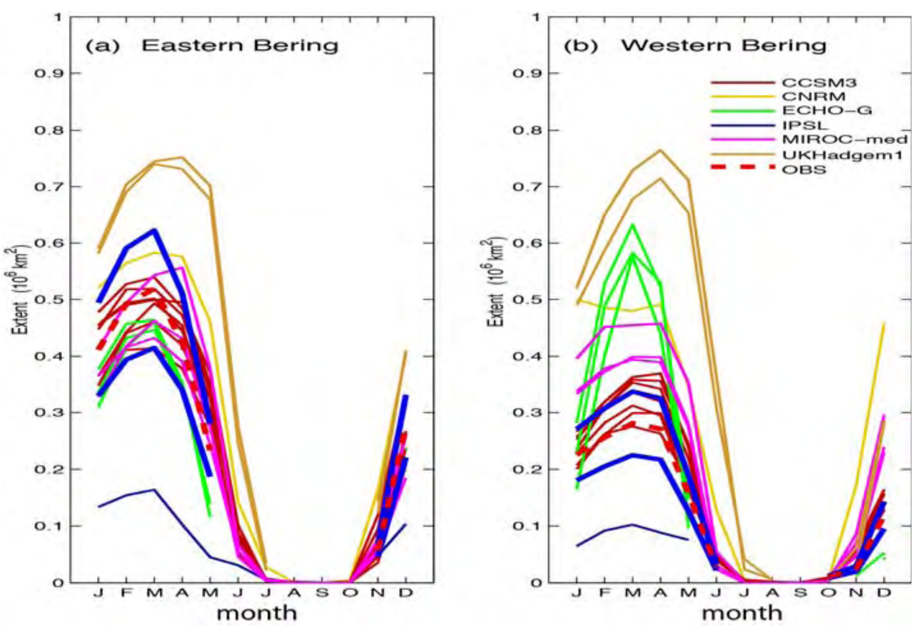

Fig. 3.9.8 Climatology of sea ice extent for (a) the eastern Bering Sea and (b) western Bering Sea. The thick red dashed line is based on observation, and the thick blues lines outline the ± 20% uncertainty around the observed value. Units are in million square kilometers.

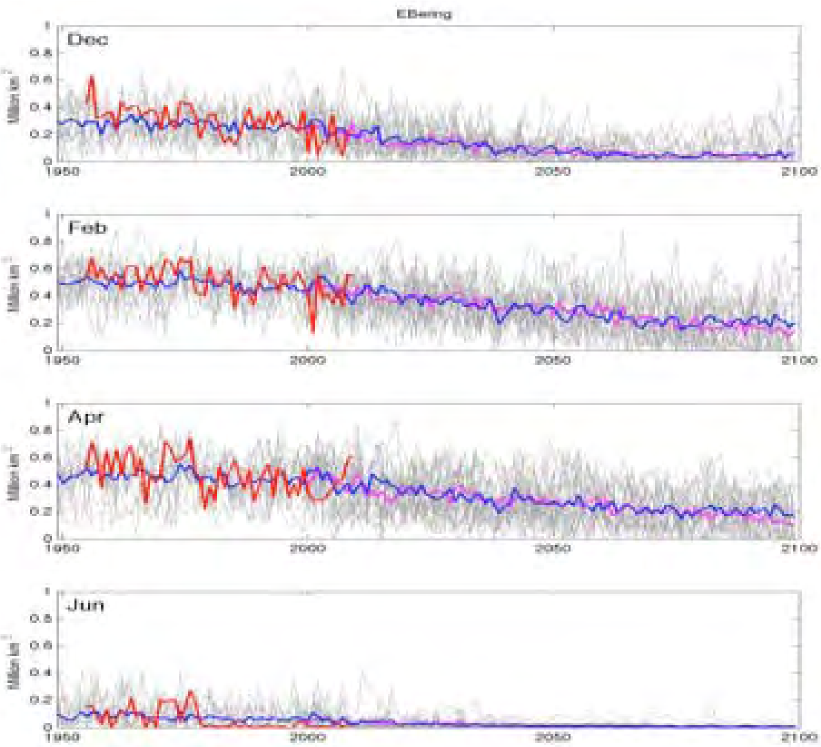

Fig. 3.9.9 Model simulated sea ice extent over the eastern Bering Sea for the months of December, February, April and June (top down). The red line is based on HadISST_ice analysis and the colored lines are the ensemble means under A1B (blue) and A2 (magenta) emission scenarios of the 4 models (CCSM3, CNRM-CM3, ECHO-G, and MIROC3.2 (medres)). Each grey line represents one realization by these models.

Summary

We suggest transparent choices regarding selection methods. In fact, one should view the process as reducing the impact of models with large hindcast error, *i.e*., culling, rather than the selection of best models, while retaining several models as a measure of model uncertainty. Credibility is gained when the model selection procedure is simple and thoroughly documented. We can recommend the following steps:

1. In many applications, it is advisable to eliminate the models that seriously fail to meet one or more observational constraints on continental scales, based on comparison with actual or synthetic data (*e.g*., reanalysis products) for climatically relevant variables such as sea level pressure, sea surface temperature, seasonal sea ice extents, or upper air variables. Do the selected variables have reasonable mean, variance, and seasonal cycle close to the observations at a continental scale or above? It bears noting that even reproducing mean quantities approximately correct is non-trivial, as the CMIP3 models are initialized in the 19th century.

2. After eliminating poorly performing models based on continental scale climate processes, the remaining subset of models is evaluated for individual variables and regions of interest. These are user selected for the problem at hand, such as a variable with an ecosystem or societal impact. Our analyses of AOGCM hindcast simulations show that models can perform differently based on region and for different variables within a region, often without obvious reasons (Overland and Wang 2007; Walsh *et al*., 2008). Nevertheless, it is plausible that the uncertainties of future climate projections would be reduced among models with better regional hindcast simulations.

3. Model uncertainty is a sampling problem, so a sample size of at least several models is desirable. Model means selected by multi-variable metrics can outperform any individual model (Walsh *et al*., 2008). Natural variability is a complicating factor in using models when only one ensemble member is available.

In general, the quality of individual model simulations depends on the variable, region, and evaluation metric. The reasons for these inconsistencies are rarely clear, which bears on the credibility of the models' results on regional scales. Nevertheless, there is certainly interest in regional projections. Further, the top-performing models for many of the cases that we have investigated tend to be more sensitive to greenhouse forcing than the poorer-performing models, suggesting that all-model means do not provide unbiased projections.

As illustrated by the examples in the preceding section, the strategy for dealing with climate model uncertainties can be keyed to several considerations. First, the available models of opportunity can be evaluated based on the ability of their 20th century hindcasts to reproduce large-scale climate variability. This variability can include the annual cycle of certain variables that are responsive to radiative forcing; it can also include leading spatial and/or temporal modes of variability. Such an evaluation serves as a climatic basis for culling some models from further consideration. Second, one can consider 20th century hindcasts of problem-relevant variables in the region of interest for further selection of models. While it may be tempting to determine a single best model and use its projections, this practice has serious risks. All climate models are subject to model uncertainty, and prior success may be fortuitous (Reifen and Toumi, 2009). Moreover, the spread in the projections from different models provides a measure of one major source of uncertainty of projections. Finally, consideration can be given to the sophistication of each model *vis-à-vis* the parameters of interest. For example, the models with more elaborate schemes for handling sea ice tended to compare better with observations, and thus have increased credibility for Arctic applications.

Acknowledgments We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support for this dataset is provided by the Office of Science, U.S. Department of Energy. JEO and MW appreciate the support of the NOAA Arctic Project, the NOAA FATE Project, and the AYK Project.

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Appendix 1

Working Group on *Evaluations of Climate Change Predictions* (WG 20) Terms of Reference

1. Analyse and evaluate climate change projections for the North Pacific and its marginal seas based on predictions from the latest global and regional models submitted to the Inter-governmental Panel on Climate Change (IPCC) for their 4th assessment report;
2. Facilitate analyses of climate effects on marine ecosystems and ecosystem feedbacks to climate by, for example computing an ensemble of the IPCC model projections for the North Pacific and making these projections available to other PICES groups such as CFAME;
3. Facilitate the development of higher-resolution regional ocean and coupled atmosphere-ocean models that are forced by, and take their boundary conditions from, IPCC global or regional models;
4. Facilitate the development of local and regional data sets (*e.g.*, SST, river flow, sea ice cover) by incorporating information from climate model projections as well as observations and historical re-analyses;
5. Ensure effective two-way communication with CLIVAR;
6. Convene workshops/sessions to evaluate and compare results;
7. Publish a final report summarizing results.

Appendix 2

Working Group on *Evaluations of Climate Change Predictions* (WG 20) Membership

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Appendix 3

Working Group on *North Pacific Climate Variability and Change* (WG 27) Terms of Reference

Approved at the 2011 Inter-sessional Science Board Meeting

Parent Committee: POC

Co-Chairmen: Michael Foreman, Shoshiro Minobe, Emanuele Di Lorenzo

Motivation:

To develop essential understandings of the mechanisms of North Pacific climate variability and change that can better guide the formulation of process-based hypotheses underlying the links between ecosystem dynamics and physical climate.

Terms of Reference:

1. Develop conceptual frameworks and low-order models of North Pacific climate variability and change, which can be used by climate researchers to investigate the mechanisms of those variations and by ecosystem scientists to explore hypotheses linking ecosystem dynamics and physical climate.
2. Summarize the current understanding of mechanisms of Pacific climate variability and change, and evaluate the strengths of the underlying hypotheses with supporting evidence.
3. In conjunction with ecosystem scientists, coordinate the development and implementation of process-based models, which include important processes in simple forms, to hindcast the variability of available long-term biological time series.
4. Develop a method to identify and provide uncertainty estimates of decadal variability in recent historical climate and ecosystem time series.
5. Provide improved metrics to test the mechanisms of climate variability and change in IPCC models, and in coordination with other PICES working groups and FUTURE Advisory Panels, assist in evaluating those models and providing regional climate forecasts over the North Pacific.
6. Understand and fill the gaps between what physical models can currently produce and what ecosystem scientists suggest are the important physical forcing factors required for predicting species and ecosystem responses to climate variability and change.
7. Maintain linkages with, and summarize the results from National and International programs/projects such as CLIVAR, IMBER, US CAMEO, ESSAS, Japanese Hot Spot in the Climate System, POMAL, CREAMS EAST-I, POBEX, and others.
8. Convene workshops and sessions to evaluate and compare results and maintain an awareness of state-of-the-art advances outside the PICES community.
9. Publish a final report summarizing results.

Appendix 4

Working Group on *Regional Climate Modeling* (WG 29) Terms of Reference

Approved at the 2011 Inter-sessional Science Board Meeting

Parent Committee: POC

Co-Chairmen: Chan Joo Jang and Enrique Curchitser

Motivation:

With the realization that physically-based future climate projections are the starting point for many socio-economic impact and adaptation considerations to future climate change and that global climate models, although they capture large scale climate behaviour, have limitations for regional assessments due to their coarse spatial resolutions, a working group is proposed to assess state-of-the-art regional climate modeling efforts, their implications for regional ecosystem studies and to further their development in the North Pacific Ocean and its marginal seas.

Terms of Reference:

1. Assemble a comprehensive review of existing regional climate modeling efforts;
2. Assess the requirements for regional ecosystem modeling studies (*e.g.*, how to downscale the biogeochemistry);
3. Continue the development of RCM implementations in the North Pacific and its marginal seas;
4. Convene special sessions and inter-sessional workshops dedicated to the RCM topic;
5. Publish report and/or review paper on best practices for regional coupled modeling;
6. Establish connections between PICES and climate organizations (*e.g.*, CLIVAR) and global climate modeling centers (*e.g.*, NCAR, JAMSTEC, CCCMA);
7. Collaborate with other PICES expert groups such as WG-27, SICCME and the FUTURE Advisory Panels possibly by producing “Outlooks”;
8. Publish a final report summarizing results.

Appendix 5

WG 20 Annual Reports

PICES Fifteenth Annual Meeting
October 13–22, 2006
Yokohama, Japan

2006 Report of Working Group on *Evaluations of Climate Change Predictions*

The Working Group (WG 20) on *Evaluations of climate change projections* held its first meeting in the afternoon of October 14, 2006. The Co-Chairmen, Drs. Michael G. Foreman and Yasuhiro Yamanaka, called the meeting to order and welcomed the participants. The meeting was attended by 10 Working Group members and 28 observers representing all PICES member countries and several international organizations (*WG 20 Endnote 1*).

The meeting began with a brief presentation by Dr. Akihiko Yatsu, Co-Chairman of the CFAME Task Team, on the objectives and progress of that group. Dr. Foreman then led a discussion on how WG 20 might collaborate with CFAME in providing climate change scenario information that would be useful for the third component (*Scenarios*) of the CFAME workplan. Drs. Arthur Miller, Emanuele Di Lorenzo and Enrique Curchitser, all members of WG 20 who have already developed high-resolution models for the California Current system that have been, or are soon to be run with climate forcing, agreed to work with Dr. Vera Agostini of CFAME in providing physical information that would be useful for her ecosystem model of that region. Dr. Hiroyasu Hasumi agreed to work with Dr. Yamanaka in providing analogous data from his climate models in the Kuroshio/Oyashio region. Dr. Ig-Chan Pang volunteered to adapt his one-tenth of a degree circulation model for the Yellow and East China Seas so that it could accept boundary and atmospheric forcing from one, or an ensemble, of IPCC global climate model scenario runs. (In subsequent discussion with Dr. Foreman he also agreed to contact Dr. Jai-Ho Oh, another WG 20 member (not present), to see if it would be feasible to use high-resolution atmospheric forcing produced by Dr. Oh's models for some of these simulations.) In the absence of a high-resolution circulation model for the Sea of Okhotsk, it was decided that an ensemble of climate model results could be provided to Dr. Victor Lapko for understanding possible changes to that ecosystem. It was not determined who would compute this ensemble, but Dr. Muyin Wang, on behalf of Dr. James E. Overland, proposed (see second paragraph below for more details) that calculations of this type be carried out for all sub-Arctic seas (including the Sea of Okhotsk) under the auspices of the GLOBEC regional program on Ecosystem Studies of Sub-Arctic Seas (ESSAS). So the ensemble might be computed in collaboration with that group.

It was also decided (subject to confirmation by CFAME and approval by Science Board) to convene a joint WG 20/CFAME workshop on "*Climate scenarios for ecosystem modeling*" at PICES XVI (*CFAME Endnote 4*). This was subsequently approved with Drs. Jacquelynne R. King and Michael G. Foreman to be the co-convenors. The suggested duration of the workshop is 1.5 days, with a format being 0.5 days with the groups separate, 0.5 days together and then 0.5 days apart again.

Dr. Kenneth Drinkwater (ESSAS SSC Co-Chairman) gave a presentation on the ESSAS goals and activities, with particular attention paid to a workshop they are organizing in June 2007, in Hakodate, Japan. Under Dr. Overland's leadership, this workshop is planning to initiate the evaluation of climate change projections for each of the ESSAS regions, and it was agreed to submit, through POC, a travel request for one WG 20 member to attend this meeting.

The issue of financial support for WG 20 members to carry out research relevant to the Terms of Reference was also briefly discussed. Dr. Foreman pointed out that although the North Pacific Research Board (NPRB) does have a request for proposals due December 1, 2006, these proposals must fall under the Board's Science Plan. As that plan does not have provision for physical or climate modeling, it precludes NPRB as a potential funding source. The Bering Sea Integrated Ecosystem Research Program of NPRB is expected to release a request for proposals soon but it remains to be seen if WG 20 activities might be supported from that source. Though WG 20 is happy to provide letters of support and generally facilitate individual members in seeking out funding from their national sources, it does not appear that there are international vehicles to provide this support.

The issue of collaborations with international organizations/programs was briefly discussed. Dr. William R. Crawford, a Canadian member of the CLIVAR Pacific Panel, stated that although this group seems primarily concerned with the tropical Pacific, it is indeed interested in the PICES region north of 30°N. It was suggested that an invitation should be extended to the CLIVAR Pacific Panel to attend the next WG 20 workshop.

The final item of discussion was a draft outline of the integrative science program, FUTURE, that PICES is hoping to initiate in the next couple of years. The latest version of the program outline was presented, and it was pointed out that the activities of WG 20 fit very well with the proposal. No specific suggestions for revisions were given but all were encouraged to attend either the POC meeting on October 18, or the Open Forum on October 19, where further discussions were planned.

WG 20 Endnote 1

Participation list

Members

Enrique Curchitser (U.S.A.)
Emanuele Di Lorenzo (U.S.A.)
Michael G. Foreman (Canada, Co-Chairman)
Hiroyasu Hasumi (Japan)
Arthur J. Miller (U.S.A.)
Ig-Chan Pang (Korea)
Elena Ustinova (Russia)
Muyin Wang (U.S.A.)
Yasuhiro Yamanaka (Japan, Co-Chairman)
Sang-Wook Yeng (Korea)

Observers

Vera Agostini (U.S.A.)
Kerim Y. Aydin (U.S.A.)
Manuel Barange (GLOBEC, U.K.)
Harold P. Batchelder (U.S.A.)
Robin M. Brown (Canada)
Rongshuo Cai (China)
Curtis Covey (U.S.A.)
William R. Crawford (Canada)
Kenneth Drinkwater (ESSAS, Norway)
Lei Gao (China)
Albert J. Hermann (U.S.A.)
George L. Hunt (U.S.A.)
Masao Ishii (Japan)
Hee-Dong Jeong (Korea)
Michi Kawamiya (Japan)
Jacquelynne R. King (Canada)
Dong-Young Lee (Korea)
Dooji Li (China)
Skip McKinnell (PICES)
Phillip R. Mundy (U.S.A.)
Keith Rodgers (U.S.A.)
Ryan Rykaczewski (U.S.A.)
Zhenya Song (China)
Ping Wang (China)
Francisco C. Werner (GLOBEC, U.S.A.)
Ichiro Yasuda (Japan)
Akihiko Yatsu (Japan)
Yury I. Zuenko (Russia)

PICES Fifteenth Annual Meeting Workshop Summary

POC Workshop (W5)
Evaluation of climate change projections

Convenors: Michael G. Foreman (Canada) and Yasuhiro Yamanaka (Japan)

Background

The most recent set of global climate model projections has been submitted to, and is being analyzed by, the Intergovernmental Panel on Climate Change (IPCC) for the publication of their Fourth Assessment Report in 2007. PICES Working Group 20 was created to evaluate these projections for the North Pacific and its marginal seas, and to compute products such as ensemble averages, that would assist PICES groups like the Climate Forcing and Marine Ecosystem Response Task Team (CFAME), in their analysis of climate effects on marine ecosystems, and ecosystem feedbacks to climate. In this workshop, presentations and discussions focused on ongoing research that addresses the Terms of Reference of the Working Group, and on strategies for future work that are needed to fill the gaps. Presentations related to the direct analysis of global climate projections and the calculation of ensemble averages; results from higher-resolution regional ocean and coupled atmosphere-ocean models that are forced by, and take their boundary conditions from the IPCC models; and the development of local and regional data sets (*e.g.*, SST, river flow, sea ice cover) based on either model projections or historical observations were solicited. The development of work/action plans, liaisons with other PICES groups and outside organizations (*e.g.*, CLIVAR), and future activities were discussed.

Summary of presentations

This workshop consisted of 3 invited talks, 11 oral presentations, and a brief business meeting that discussed future activities of the Working Group 20. In a brief introduction, Michael Foreman welcomed all participants, outlined the agenda for the day, and reviewed the Terms of Reference of WG 20. Yoshiro Yamanaka then introduced all speakers for the morning part of the session.

The first invited speaker, Curtis Covey, briefly described his experience in managing and using the archive of climate model output created by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory for the IPCC Fourth Assessment Report (AR4). He summarized the IPCC objectives, including the release of their upcoming report and plans for adding biogeochemistry to the next generation of climate models, and gave two interesting examples of analyses arising from the model output. The next speaker, Hiroyasu Hasumi, presented an overview of results from two CCSR/NIES/FRCGC (Japan) climate models, one of which has the highest spatial resolution of all the IPCC models. His presentation focused on analyses aimed at understanding the different results that arise from this finer resolution. His ongoing comparison among high and medium resolution ocean general circulation models (OGCMs) with the same atmospheric forcing will provide useful information for constructing regional high resolution models forced by one, or an ensemble, of IPCC global climate model scenario runs. Muyin Wang next presented results from an analysis of IPCC models showing that a basin wide warming signal under the IPCC SRES A1B scenario is predicted to surpass the Pacific Decadal Oscillation as the leading mode of variability in the North Pacific in the next forty years. The spatial pattern of the model-projected temperature trends is more uniform than the east-west dipole pattern of the PDO. Michael Foreman briefly summarized the major results of 11 recently published papers, each of which presented direct or derived results from individual or ensembles of climate models for the North Pacific. The results covered changes in oceanic properties ranging from sea surface temperature and salinity to the Rossby radius of deformation and shoaling of the depth at which calcifying organisms dissolve. However, there was not always consensus among the models. The final speaker before the morning coffee break, Rong-Shuo Cai, described observed climate changes in the East and South China seas over the last 50 years. These included a weakening of the summer and winter winds, increases in the sea surface temperature, and more frequent occurrences of red tides.

The morning session after coffee began with a second invited speaker, Michio Kawamiya, describing the positive feedback that arises when carbon cycle interactions are included in climate change models, and the inter-comparison project, Coupled Climate Carbon Cycle Model Intercomparison Project (C4MIP), that seeks to understand the differing results among various models that incorporate this cycle. Another invited speaker, Keith Rodgers, followed with description of his modelling study of variability in equatorial Pacific biogeochemistry and ecosystems, for which a major result was a de-coupling of the pycnocline and nutricline. He pointed out a difference in simulated iron supply associated with equatorial upwelling between two re-analyse data sets: National Centers for Environmental Prediction (NCEP) and European Centre for Medium-range Weather Forecasts (ECWMF), especially after the 1970s. Sang-Wook Yeh next described differences in observed sea surface temperatures warming trends in the North and Equatorial Pacific over epochs extending from the early 1900s to the present. The final speaker of the morning, Zhenya Song, demonstrated the importance of including the mixing from surface waves in global model simulations by comparing climatological observations with model results.

The first speaker in the afternoon, Elena Ustinova, described spectral analyses of, and correlations between, time series of sea ice extent and air and water temperature in the Okhotsk and eastern Bering Seas. William Crawford followed with an analysis of 50 years of salinity and temperature observations along Line-P. His main result was that many changes are strongly related to changes in the predominant wind direction. Hee-Dong Jeong carried out a similar analysis of 37 years of temperature observations around the Korean Peninsula, finding different trends in three sub-regions and in different depth ranges. Masao Ichii then described analyses of observations of total inorganic carbon and dissolved oxygen along the 165°E transect between 28°N and 50°N. His results suggested that changes were more likely due to variability in the circulation or biogeochemistry rather than the uptake of CO_2. The final speaker, Dong-Young Lee, described the problems associated with estimating design wave heights in light of climate change.

List of papers

Oral presentations

Curtis Covey (Invited)
Managing, using and expanding the IPCC database of climate model output

Hiroyasu Hasumi and Takashi T. Sakamoto
Overview of the present state and future projection of North Pacific climate simulated by CCSR/NIES/FRCGC global coupled models

Muyin Wang, James E. Overland and Nicholas A. Bond
What will the North Pacific look like in the next 40 years?

Michael G. Foreman
Highlights from recent publications describing climate projections for the North Pacific

Rong-Shuo Cai, Ji-Long Chen and Rong-Hui Huang
The response of marine environment in the offshore area of China and its adjacent ocean to recent global climate change

Michio Kawamiya, Chisato Yoshikawa, Tomomichi Kato and Taroh Matsuno (Invited)
Significance of ocean's response to climate warming in the global carbon cycle

Keith B. Rodgers, Christophe Menkes, Thomas Gorgues, Laurent Bopp and Olivier Aumont (Invited)
A modeling study of interannual to decadal variability in Equatorial Pacific biogeochemistry and ecosystems

Sang-Wook Yeh, Cheol-Ho Kim, Young-Gyu Park and HongSik Min
Characteristics of Pacific sea surface temperature variability associated with global warming during the 20th century

Zhenya Song and Fangli Qiao
The establishment of the atmosphere-surface wave-ocean circulation coupled numerical model and its applications

Elena I. Ustinova
Evaluation of climatic variability in the Far-Eastern Seas using regional data sets

William Crawford, Jake Galbraith and Nick Bolingbroke
Temperature and salinity along Line-P: Fifty years of observations

Hee-Dong Jeong, In-Seong Han, Ig-Chan Pang, Ki-Tack Seong, Woo-Jin Go, Sang-Woo Kim, Won-Deuk Yoon, Yong-Kyu Choi and Jun-Yong Yang
Seasonal long-term variation of temperature in Korean waters

Masao Ishii, Takayuki Tokieda, Shu Saito, Takashi Midorikawa, Shinji Masuda and Akira Nakadate
Decadal trend of dissolved oxygen in the North Pacific along 165ºE – A preview

Dong-Young Lee and K.C. Jun
Estimation of design wave height through long-term simulation of sea states for the North East Asia regional seas

PICES Sixteenth Annual Meeting
October 26–November 5, 2007
Victoria, Canada

2007 Report of Working Group 20 on *Evaluations of Climate Change Predictions*

The Working Group on *Evaluations of Climate Change Projections* (hereafter WG 20) held its second meeting from 14:00–18:00 hours on October 27, 2007. After introductory formalities to members and observers (*WG 20 Endnote 1*) were conducted by Co-Chairmen, Drs. Michael G. Foreman and Yasuhiro Yamanaka, the draft agenda was reviewed and adopted without changes (*WG 20 Endnote 2*). Dr. Muyin Wang agreed to serve as the rapporteur.

Discussion of a workshop with CFAME and update on Terms of Reference (Agenda Items 3 and 4)

The meeting began with a discussion of the recently concluded joint workshop on "*Climate scenarios for ecosystem modeling*" (W6) with the Climate Forcing and Marine Ecosystems Task Team (CFAME). The following was requested by CFAME from WG 20, preferably by their inter-sessional meeting in April 2008 and certainly by their final meeting in October 2008:

1. Graphic representations of climate/ocean states under climate warming for each of the three ecosystems selected by CFAME. For the Kuroshio/Oyashio, this representation will be based on detailed model results available from a high-resolution Japanese global climate model to which Dr. Yamanaka has coupled his biological COCO–NEMURO model. For the California Current System, this representation will be based on either results from a high-resolution Regional Ocean Model System (ROMS) climate model, or if this is not available, from downscaled global climate model values. For the Yellow and East China Seas, this graphic will also be based on either regional climate model output or downscaled values from global climate models.
2. Detailed output from Dr. Yamanaka's COCO–NEMURO model simulations for the Kuroshio/Oyashio region for 2007–2030 (or whatever projection time period he chooses).
3. A comparison of the atmospheric component in the Japanese high-resolution Model for Interdisciplinary Research on Climate (MIROC) with other climate models to assess the range of variability and determine any biases that could potentially affect the results arising from (2) above.
4. Climate change variables (such as SST, stratification, circulation) for the California Current System (north, central and south sub-regions) that have either been taken from regional climate models, or downscaled from global climate models.

The second and fourth requests were viewed as potentially longer-term products that could be included in the CFAME final report to provide future PICES groups with relevant climate parameters. Dr. Foreman will work with regional representatives in coordinating delivery of the first request. Dr. Yamanaka will work on the second, Drs. Wang and James E. Overland will work on the third, and Dr. Foreman will work with Drs. Wang, Overland, Enrique Curchitser, Arthur J. Miller and Emanuele Di Lorenzo on the fourth. It was also reported that CFAME will invite the WG 20 Co-Chairmen to attend their inter-sessional meeting in Honolulu in April 2008 (*CFAME Endnote 3*) in order to receive immediate feedback on revised descriptions of relevant physical processes for the three selected ecosystems.

In addition to the updates on WG 20 activities, Dr. Miller gave a short presentation on a recent climate workshop on "*The known, unknown, and unknowable*" at the Scripps Institution of Oceanography, and Dr. Young-Gyu Park provided an update on his regional Finite Volume Coastal Ocean Model (FVCOM) for the waters surrounding Korea.

Next major PICES scientific program (Agenda Item 5)

A lively discussion took place on the latest draft (version 4.2) of a Science Plan for a new PICES integrative scientific program on **F**orecasting and **U**nderstanding **T**rends, **U**ncertainties and **R**esponses of North Pacific Marine **E**cosystems (FUTURE). Dr. Foreman felt that physical and geochemical issues were not given sufficient recognition in the Science

Plan for the role they will be playing in providing forecasts (and associated uncertainties) of ecosystems that are changing due to climate and other anthropogenic effects. Possible revisions to key and secondary questions were discussed and general agreement was given to a draft presentation by POC at the FUTURE Open Forum on November 1.

Future WG 20 workshops and meetings (Agenda Item 6)

Dr. Foreman briefly described the upcoming International Symposium on the "*Effects of climate change on the world's oceans*" to be convened May 19–23, 2008, in Gijón, Spain. PICES has booked a room so that WG 20 can hold an informal meeting at this symposium if a sufficient number of members attend. The invitation to participate in this meeting was also extended to CFAME members.

CFAME has expressed interest in holding another joint workshop with WG 20 on "*Climate scenarios for ecosystem modeling II*" at the 2008 PICES Annual Meeting (*CFAME Endnote 4*). Dr. Gordon A. (Sandy) McFarlane (CFAME) will be co-convening the workshop with either Dr. Foreman or Dr. Yamanaka.

Items with financial implications (Agenda Item 7)

Travel support was requested for:

- one WG 20 member to attend the next ESSAS Annual Meeting to be held in September 2008, in Halifax, Canada;
- Dr. Foreman to attend the Gijón Symposium where he will be co-convening a session on "*Past and future variability and change in ocean climate: Climate model projections*".

Other business (Agenda Item 8)

No other business was discussed.

WG 20 Endnote 1

Participation list

Members

Enrique Curchitser (U.S.A.)
Emanuele Di Lorenzo (U.S.A.)
Michael G. Foreman (Canada, Co-Chairman)
Hiroyasu Hasumi (Japan)
Arthur J. Miller (U.S.A.)
Young-Gyu Park (Korea)
Muyin Wang (U.S.A.)
Elena Ustinova (Russia)
Yasuhiro Yamanaka (Japan, Co-Chairman)

Observers

Yong-Kyu Choi (Korea)
Albert J. Hermann (U.S.A.)
Phillip R. Mundy (U.S.A.)
Thomas C. Royer (U.S.A.)

WG 20 Endnote 2

WG 20 meeting agenda

1. Welcome, introductions, opening remarks
2. Adoption of agenda and appointment of rapporteur
3. Discussion of, and action items arising from, a workshop with CFAME
4. Updates on work related to WG 20 Terms of Reference
5. Discussion on the next major PICES scientific program, FUTURE: Roles for WG 20 and respective member countries
6. Future WG 20 workshops/meetings
   (i) Climate Change Symposium, Gijón, Spain, May 2008
   (ii) PICES XVII, Dailan, China, Oct.–Nov. 2008
   (iii) other?
7. Items with financial implications
   (i) Travel support requests:
      a. ESSAS Annual Meeting, Halifax, September 2008
      b. Climate Change Symposium, Gijón, Spain, May 2008
   (ii) Other items
8. Other business
9. Adoption of report for presentation at POC committee meeting

PICES Sixteenth Annual Meeting Workshop Summary

POC/CCCC Workshop (W6)
Climate scenarios for ecosystem modeling

Co-Convenors: Jacquelynne R. King (Canada) and Michael G. Foreman (Canada)

Background

The objective of this workshop was to facilitate discussion between CFAME and Working Group on *Evaluations of Climate Change Projections* (WG 20) on potential future collaborative research on forecasting the impacts of climate change (as represented by IPCC projection scenarios) on regional ecosystems and species of the North Pacific. The workshop began with overviews of the Terms of Reference and workplans for CFAME and WG 20 by their Co-chairmen, Kerim Aydin (CFAME) and Michael Foreman (WG 20). The overviews provided the context for overlap in research foci between these two groups. CFAME has focused on three North Pacific ecosystems that represent different dominant physical processes: 1) California Current System (boundary current with upwelling); 2) Kuroshio/Oyashio Current System (boundary currents); 3) Yellow Sea/East China Sea Region (freshwater input). For each ecosystem, CFAME has developed conceptual models of the mechanisms relating climate forcing to the population dynamics of key species and to ecosystem processes. One of the goals of WG 20 is to facilitate analyses of climate effects on marine ecosystems and ecosystem feedbacks to climate by, for example, computing an ensemble of the IPCC model projections for the North Pacific and making these projections available to other PICES groups such as CFAME. The analyses could provide forecasts of regional parameters (such as sea surface temperature, sea ice cover, and river discharge) relevant to ecosystem processes identified within CFAME's conceptual models.

Summary of presentations

Thirteen talks were presented by CFAME and WG 20 members from Canada, Japan, Korea and the United States. Presentations were organized by the three ecosystems that CFAME has focused on. For each ecosystem a brief overview was presented by a CFAME member, providing a summary of the key processes that define the seasonal or temporal variability in physical parameters. In addition, each presentation quickly introduced some of the key species in the lower and higher trophic levels of each system.

CFAME members presented the conceptual models that they have developed for the mechanisms linking physical processes to population dynamics. Following these presentations, WG 20 members presented results of recent climate and oceanographic modelling efforts relevant to each of the three ecosystems. To wrap up the information portion of the workshop, a presentation on synthesis, and summary of the key climate and oceanographic factors required for ecosystem projections given climate change, was made, followed by a presentation on the uncertainties in climate model ensemble projections.

Discussion on the first day highlighted the need for CFAME to define geographic regions (*e.g.*, spawning areas, zone within an ecosystem) and to provide the important physical parameters that affect population dynamics (*e.g.*, stratification in the California Current System). Despite the broad definitions used in the ecosystem conceptual models, key processes were identified for each ecosystem. For the California Current System, temperature and its spatial variability, stratification, transition timing to upwelling, upwelling intensity, and eddies/meanders in the alongshore current. Characteristics of upwelling could be represented by upwelling favourable winds. Characteristics of currents will be a difficult feature to provide from existing climate/ocean modelling efforts because of their coarse resolution. In the Kuroshio/Oyashio System, key physical processes included temperature and its spatial variability, location of the southern branch of the Oyashio, location of the Kuroshio and its eddies/meanders. In addition, a key predator (Japanese common squid) is impacted by temperature and salinity (*i.e.*, pycnocline) in the East China Sea. High resolution climate models have been developed for the Kuroshio/Oyashio System and these parameters, including characteristics in the Kuroshio (*i.e.*, extent of meanders), could be forecasted. The East China Sea is not well represented by climate models, mainly because of the dominant influence of freshwater input.

Key processes identified for the Yellow Sea/East China Sea system included temperature and salinity. On the second day of the workshop CFAME and WG 20 met separately to discuss the previous days' discussion and to formulate workplans, and the outcomes are reported in the annual reports of each group.

List of papers

Oral presentations

Emanuele Di Lorenzo (WG 20 member, Invited) **and Niklas Schneider**
A North Pacific gyre-scale oscillation: Mechanisms of ocean's physical-biological response to climate forcing

Gordon McFarlane (CFAME member, Invited)
Conceptual mechanisms linking physical and biological oceanography to population dynamics of key species in the California Current System

Akihiko Yatsu, Yoshiro Watanabe (CFAME members, Invited)**, M. Kaeriyama, Y. Sakurai and A. Nishimura** (Presented by Jacquelynne King)
Conceptual mechanisms linking physical and biological oceanography to population dynamics of key species in the Kuroshio/Oyashio Current System

Yeong Hye Kim (Invited)
Conceptual mechanisms linking physical and biological oceanography to population dynamics of key species in the Yellow Sea/East China Sea

Jinhee Yoon, K.-I. Chang, Takashi T. Sakamoto, Hiroyasu Hasumi and Young Ho Kim
Effects of global warming on the East/Japan Sea heat balance using a global climate model (MIROC3.2-hires)

Enrique Curchitser (WG 20 member, Invited)
Embedding a high-resolution California Current climate model into the NCAR global climate model

Taketo Hashioka, Yasuhiro Yamanaka, Takashi T. Sakamoto and Maki N. Aita
Future projection with a 3-D high-resolution ecosystem model

Michael Foreman (WG20 member, Invited)
Future winds off the BC coast

Vera Agostini (CFAME member, Invited)
Overview of the California Current System

Akihiko Yatsu (CFAME member, Invited)**, Tsuneo Ono, Kazuaki Tadokoro** (CFAME member)**, Akira Nishimura, Shin-ichi Ito, Sanae Chiba and Yasunori Sakurai**
Overview of the Kuroshio/Oyahsio Current System

Young Shil Kang (CFAME Co-Chairman, Invited)
Overview of the Yellow Sea/East China Sea

James Overland (CFAME member, Invited)
Synthesis and summary of key climate and oceanographic factors identified by CFAME and required for ecosystem projections given climate change

Muyin Wang (W20 member, Invited)
Uncertainties in climate model ensemble projections

PICES Seventeenth Annual Meeting
October 24–November 2, 2008
Dalian, People's Republic of China

2008 Report of Working Group 20 on *Evaluations of Climate Change Predictions*

The Working Group on *Evaluations of Climate Change Projections* (hereafter WG 20) held its third meeting from 14:00–15:30 hours on October 25, 2008. After introductory formalities to members and observers (*WG 20 Endnote 1*) were conducted by Co-Chairmen, Drs. Michael G. Foreman and Yasuhiro Yamanaka, the draft agenda was reviewed and adopted without changes, and Dr. Enrique Curchitser kindly agreed to serve as rapporteur (*WG 20 Endnote 2*).

AGENDA ITEMS 3 AND 4
Discussion of action items arising from a workshop with CFAME, and update on Terms of Reference

The meeting began with a recap of the WG Terms of Reference (*WG 20 Endnote 3*) and an assessment of what had been achieved thus far. In light of the presentations by Drs. James Overland/Muyin Wang, James Christian, Emanuele Di Lorenzo, and Curchitser, Foreman and Yamanaka, at the workshop on "*Climate scenarios for ecosystem modeling*" (W4), it was felt that with the exception of items 4, 5, and 7, considerable progress had been made in all objectives.

With regard to the collaboration with CFAME (Climate Forcing and Marine Ecosystem Response), whose tenure as a Task Team ended at this PICES meeting, Dr. Foreman briefly described the assignments/homework arising from the CFAME inter-sessional workshop on "*Linking and visualizing climate-forcing mechanisms and marine ecosystem changes: A comparative approach*" held April 15–17, 2008 in Hawaii and the Task Team's goal of completing their final report by year end. With regard to CFAME's subproject on the California Current Ecosystem, Dr. Foreman stated that a recent email from CFAME member, Dr. Vera Agostini, requested information on projected changes to the stratification, temperature, river discharge, currents (*e.g.*, undercurrent), eddies/meanders, winds (in relation to turbulence, upwelling, deep mixing), tidal mixing for (if possible), the northern, central, and southern subregions of the system. Though it was generally agreed one or more regional climate models with sufficiently high resolution would be needed to provide these projected changes with some degree of confidence, at present these models do not exist. Nevertheless, an intermediate step that should yield sufficiently accurate estimates for these variables would be the statistical downscaling of global climate model values that has been described in PICES workshops and sessions by Wang/Overland/Bond and Pal/Merryfield/Morrison/Foreman. It was further agreed that the two variables for which it would be most difficult to provide change estimates would be the undercurrent (its underlying dynamics and variability are still not fully understood) and eddies/meanders (though it might be possible to estimate these changes by running existing regional models with higher heat fluxes, this could not be done in the time frame needed by CFAME). It was resolved that Drs. Foreman, Overland, and Wang would do their best to provide the information that Dr. Agostini needed. For the other two CFAME ecosystems, Dr. Yamanaka agreed that he would work with Dr. Sanae Chiba in providing the necessary information for the Kuroshio/Oyashio system while Dr. Young-Shil Kang would work with Dr. Jae-Bong Lee in providing the necessary information for the Yellow and East China Seas system.

AGENDA ITEM 5
FUTURE Implementation Plan

Following a brief summary of the latest draft of the FUTURE Implementation Plan, a lively discussion followed on the roles of WG 20 and a possible follow-up working group. Though WG 20 was scheduled to complete its tenure at the 2009 PICES Annual Meeting, it was felt that the downscaling requirements of the FIS/POC proposed new Working Group on "*Forecasting Climate Change Impacts on Fish and Shellfish*" should justify asking POC and Science Board for a one year extension. After that, it was felt that a new working group whose mandate would be to investigate the predictability of internannual to decadal variability might be warranted. Toward that end, it was decided that Dr. Di Lorenzo would work with Drs. Overland and Foreman in developing a proposal for a topic session along those lines for the next PICES Annual Meeting. (See *WG 20 Endnote 4* for the final proposal. Note that at the Science Board meeting on November 1, this proposed Topic Session was switched to a workshop to be scheduled before the main PICES-2009 Annual Meeting.) The success of that session would determine whether or not POC should proceed in creating the new working group.

AGENDA ITEMS 6, 7, 8
Final report, future workshops/meetings, items with financial implications

Other issues discussed are as follows:

1. Though extending WG 20 for another year forestalls planning the final report, it was agreed that we should be thinking of how that report should be structured. It is hoped that all WG 20 members could provide summaries of their work relevant to the Terms of Reference.
2. Even with an extension of WG 20's lifetime, the development, testing, and evaluation of regional climate models will go beyond the tenure of WG 20. So a new home needs to be found for this activity – perhaps within one of the new FUTURE Task Teams.
3. An informal WG 20 progress report meeting will be scheduled for those members attending the GLOBEC Open Science Meeting in Victoria, Canada in June 2009.
4. A new zooplankton working group (Working Group (WG 23) on *Comparative Ecology of Krill in Coastal and Oceanic Waters around the Pacific Rim*) might also be asking for climate change estimates relevant to their research. In order to respond to this request and perhaps others like it in the future, it might be possible to create an archive of downscaled results on some web server.
5. It was agreed that WG 20/POC would support Dr. Anne Hollowed's proposal for the creation of a new Working Group on "*Forecasting Climate Change Impacts on Fish and Shellfish*". See *WG 20 Endnote 5* for the background and Terms of Reference.
6. It was also agreed that WG20/POC needs to continue emphasizing the fact that the physics cannot be assumed done in FUTURE activities. Work needs to continue in better understanding the physical dynamics (*e.g.*, interannual to decadal variability) relevant to ecosystems.

AGENDA ITEM 9
Other business

No other business was discussed and the meeting was adjourned.

WG 20 Endnote 1

WG 20 participation list

Members

James Christian (Canada)
Enrique Curshitser (U.S.A.)
Emanuele Di Lorenzo (U.S.A.)
Michael G. Foreman (Canada, Co-Chairman)
Elena Ustinova (Russia)
Muyin Wang (U.S.A.)
Yasuhiro Yamanaka (Japan, Co-Chairman)
Sang-Wook Yeh (Korea)

Observers

Guoqi Han (Canada)
Albert J. Hermann (U.S.A.)
Masahide Kaeriyama (Japan)
Oleg Katugin (Russia)
David L. Mackas (Canada)
James E. Overland (U.S.A.)
Jake Schweigert (Canada)
John E. Stein (PICES)
Akihiko Yatsu (Japan)

WG 20 Endnote 2

WG 20 meeting agenda

1. Welcome, introductions, opening remarks
2. Changes to, adoption of, agenda and appointment of rapporteur
3. Discussion of, and action items arising from, workshop with CFAME and new fisheries WG
4. Updates on work related to WG Terms of Reference
    a. Shopping list for CFAME
    b. Additional presentations to those in W4
    c. Other
5. Discussion of FUTURE Implementation Plan: Roles for WG 20, its successor (?), and respective member countries
6. WG 20 final report: discussion, publications, work assignments
7. Future WG 20 workshops/meetings
    a. Before or after GLOBEC Open Science Meeting in Victoria, June 22–26, 2009?
    b. Final meeting and/or workshop/session at PICES-2009, Jeju, Korea, October 2009
    c. Other?
8. Items with financial implications
    a. Travel support requests:
        (i) Invited speaker for June 2009 meeting?
    b. Other items
9. Other business
10. Adoption of report for presentation at POC committee meeting

WG 20 Endnote 3

Terms of Reference

1. To analyze and evaluate climate change projections for the North Pacific and its marginal seas based on predictions from the latest global and regional models submitted to the Inter-governmental Panel on Climate Change (IPCC) for their 4th assessment report;
2. To facilitate analyses of climate effects on marine ecosystems and ecosystem feedbacks to climate by, for example computing an ensemble of the IPCC model projections for the North Pacific and making these projections available to other PICES groups such as CFAME;
3. To facilitate the development of higher-resolution regional ocean and coupled atmosphere-ocean models that are forced by, and take their boundary conditions from, IPCC global or regional models;
4. To facilitate the development of local and regional data sets (*e.g.*, SST, river flow, sea ice cover) incorporating information from climate model projections as well as observations and historical re-analyses;
5. To ensure effective two-way communication with CLIVAR;
6. To convene workshops/sessions to evaluate and compare results;
7. To publish a final report summarizing results.

WG 20 Endnote 4

Proposal for a 1-day Topic Session for PICES-2009 on
"Exploring the predictability and mechanisms of Pacific low frequency variability beyond interannual timescales" [later changed to a workshop]

Introductory lecture
M. Foreman (POC) – "*Overview of current understanding of Pacific Ocean climate variability*"

Understanding the dynamics that control climate variability in the Pacific basin is essential for exploring the degree of predictability of the ocean–atmosphere and sea–ice climate systems of the North Pacific. The goal of this session is to improve the conceptual and quantitative frameworks used by the PICES community to interpret low-frequency climate variability in the Pacific basin, ranging from interannual to multi-decadal timescales. We invite contributions on a broad range of topics including (1) studies that link regional to basin scale dynamics, (2) investigations of “regime shift”, specifically the extent to which sharp transitions in the climate system are predictable and connected with low-frequency variations in the ocean–atmosphere and sea–ice systems, (3) studies that separate the stochastic and deterministic components of low-frequency climate fluctuations, (4) analysis of long-term observations collected in regional environments across the Pacific, specifically their relationship to large-scale climate processes as opposed to local scale dynamics, (5) climate change and how it may impact the statistics of Pacific climate (*e.g.*, frequency of “regime shifts”) and (6) more generally, studies that propose new mechanisms underlying low-frequency Pacific climate variability.

Sponsor: POC

Convenors: Emanuele Di Lorenzo (U.S.A.), Shoshiro Minobe (Japan)

Recommended Invited Speakers
John Fyfe, William Merryfield or Kenneth Denman (Canada) – climate modelling;
Tim Barnett or David Pierce (U.S.A.) – Pacific decadal variability and climate change;
Nicolas Gruber (Switzerland) – mechanism of global biogeochemical cycles;
other speakers from Japan, U.S.A. or Korea TBD.

Session Organization
1. Dr. Minobe and Di Lorenzo have agreed to convene the session.
2. The session will open with a 40-minute overview of the current theories and understandings of Pacific climate variability. The overview will be given by Dr. Foreman (POC) with contributions from several authors.
3. The session will last for no longer than one day.
4. We plan to have four invited speakers representing the countries involved in PICES. The goal is to use the invited speaker slots to invite and attract scientists who are currently not involved in PICES but who can bring new insights to the PICES community in terms of Pacific climate variability and climate change.

WG 20 Endnote 5

Proposal for a new PICES/ICES Working Group on
***Forecasting Climate Change Impacts on Fish and Shellfish* (WG-FCCIFS)**

Proposed Parent Committees
ICES approved the formation of WG-FCCIFS as a permanent working group. FIS will serve as the parent committee for WG-FCCIFS with support from POC. The activities of WG-FCCIFS may be integrated into the PICES FUTURE program as a task team. WG-FCCIFS will report to the ICES Climate Change Steering Group, ICES Oceanography Committee, and the PICES FIS and POC Committees.

Suggested Co-Chairmen
Anne Hollowed (U.S.A.)
Manuel Barange (UK)
Suam Kim (Korea)
Harald Loeng (Norway)

Suggested Working Group members
Richard Beamish – Canada (NPAFC, PICES FIS)
Daniel Duplisea – Canada (ICES)
Thomas Okey – Canada (PEW Trust)
Michael Foreman – Canada (PICES POC)
Keith Brander – Denmark (ICES, IPCC ecosystem writing team)
Jürgen Alheit – Germany (ICES, GLOBEC SPACC)
Shin-ichi Ito – Japan (ESSAS, PICES POC)

Sang-Wook Yeh - Korea
Jason Holt - UK (QUESTFISH, ICES),
James Overland – U.S.A. (ESSAS, PICES POC)

Rationale
The work of WG-FCCIFS is essential to ensure that ICES and PICES will be able to provide guidance on the potential impacts of climate change on marine ecosystems and the response of commercial fish and shellfish resources to these changes.

The work done within ICES and PICES on climate change and fisheries has been diverse and has included: a) guidance on methods for selection of IPCC models under different emission scenarios for use in projections; b) techniques for downscaling IPCC model outputs to local regions, c) development of coupled ecosystem models for use in evaluating climate-induced shifts in environmental conditions, d) literature documenting relationships between climate forcing and marine fish and shellfish distribution and production, and e) stock assessment techniques for evaluating management strategies to mitigate the impacts of change. A challenge facing ICES and PICES is the need to integrate all of this research to provide stakeholders with quantitative estimates of the potential impact of climate change on marine life throughout the world. This challenge calls for the establishment of an interdisciplinary research team composed of experts from around the world who will focus attention on the development of common and standardized frameworks for forecasting climate change impacts on marine life, with particular emphasis on commercially important fish and shellfish. ICES and PICES should act now to ensure that our research communities develop the capibilities to provide quantitative contributions to the next IPCC reports and to provide guidance for management under climate change scenarios.

Several case studies will be identified by the Steering Group based on their potential for contributing to methodological development and the opportunity for comparison of marine species and community responses to climate forcing in different ecosystems. Members of the Working Group will be responsible for encouraging the development of regional interdisciplinary teams responsible for the production of forecasts. Members of the Working Group will provide guidance to the regional teams by providing a framework for the development of the forecasts and communication of new advances in analytical tools. The culmination of the Working Group's effort will be presentation and discussion of results at an inter-sessional meeting and publication of results in a peer reviewed journal by 2011. The timing for the publication is critical because the future IPCC AR5 report is slated for release in 2013 and the IPCC only allows references to published papers.

Proposed Terms of Reference

We recommend that WGFCCIFS is established to promote and coordinate research on the potential impacts of climate change on marine fish and shellfish around the world.
The Working Group will:

1. Promote research on climate change impacts on fish and shellfish by scientists in ICES and PICES member nations through coordinated communication, exchange of methodology, and organization of meetings to provide a venue for discussion and publication of results.
2. Develop frameworks and methodologies for forecasting the impacts of climate change on the growth, distribution and abundance of marine life with particular emphasis on commercial fish and shellfish;
3. Review the results of designated case studies to test methods;
4. Hold an inter-sessional symposium in early 2010 where scientists can present, discuss and publish forecasts of climate change impacts on the world's commercial fish and shellfish resources;
5. Establish techniques for estimating and communicating uncertainty in forecasts;
6. Evaluate strategies for research and management under climate change scenarios, given the limitations of our forecasts;
7. Produce publications that could be considered for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change in 2013;
8. Publish a final report summarizing work.

The Working Group will utilize web technology to hold several virtual Working Group meetings. They will hold an inter-sessional Working Group meeting on June 21, 2009 one day prior to the GLOBEC Open Science meeting in Victoria, Canada. At that meeting members will review the results of designated case studies and discuss a symposium for 2010. WG-FCCIFS will report by September 2009 for the attention of the ICES Climate Change Steering Group, ICES Oceanography Committee, and the PICES FIS and POC Committees. WG-FCCIFS will provide several case studies that will contribute to the PICES FUTURE program.

Working Group members will seek widened participation for this group, including contact with relevant academic and inter-governmental organizations such as fisheries managers, the North Pacific Anadromous Fish Commission, the Intergovernmental Oceanographic Commission, and FAO for the symposium in 2010.

PICES Seventeenth Annual Meeting Topic Session Summary

CCCC/POC/FIS Workshop (W4)
Climate scenarios for ecosystem modeling (II)

Co-Convenors: Michael G. Foreman (Canada), Anne B. Hollowed (U.S.A.), Suam Kim (Korea) and Gordon McFarlane (Canada)

Background

Members of the Climate Forcing and Marine Ecosystem Task Team (CFAME), the Working Group on Evaluations of Climate Change Projections (WG 20), and the FIS Committee presented the results of their research on developing and applying the output of regional and global climate scenarios to ecosystem and fish stock forecasts. These groups have been developing conceptual and empirical models of the mechanisms that link climate variation to the dynamics of marine ecosystems and their commercially important species. Their work has focused on comparisons among a diversity of North Pacific ecosystems with differing dominant physical processes. WG 20 is developing higher resolution regional coupled atmosphere–ocean models forced by IPCC global or regional models to provide forecasts of regional parameters (such as SST, sea ice cover, and river discharge) that are relevant to ecosystem processes. This workshop provided an opportunity to discuss the results, present them to the PICES community, and describe their potential for the FUTURE Program.

List of papers

Oral presentations

Thomas A. Okey, Anne B. Hollowed, Michael J. Schirripa and Richard J. Beamish (Invited)
The 2035 modelling challenge for forecasting climate impacts on marine biota and fisheries: A collaboration emerging from an international workshop

James E. Overland, Muyin Wang and Nicholas A. Bond
Utility of climate models for regional ecosystem projections

Young Shil Kang and Sukgeun Jung
Regional differences in responses of meso-zooplankton to long-term oceanographic changes in Korean sea waters

Yasuhiro Yamanaka *et al.*
(WG 20 update): Recent results connecting climate change to fish resources using the high resolution model, COCO-NEMURO

Emanuele Di Lorenzo, N. Schneider, K.M. Cobb, K. Chhak, P.J.S. Franks, A.J. Miller, J.C. McWilliams, S.J. Bograd, W.J. Arango, H. Sydeman, E. Curchister, T.M. Powell and P. Rivere
(WG 20 update): North Pacific Decadal Variability in the FUTURE

James Christian
(WG 20 update): Canadian Earth System Model scenarios for the North Pacific

Qigeng Zhao, Qingquan Li, Jianglong Li and Fanghua Wu
A simulation of acidification in the Pacific Ocean

Enrique Curchitser, William Large, Jon Wolfe and Kate Hedstrom
(WG 20 update): Downscaling climate scenarios with a fully coupled global-to-regional model

Michael G. Foreman, William J. Merryfield, Badal Pal and Eric Salathé
An update of regional climate modelling along the British Columbia Shelf

Vadim Navrotsky
(WG20 update): On the role of ocean and land living matter in Global Climate Change

Anne B. Hollowed, Teresa A'mar, Richard J. Beamish, Nicholas A. Bond, James E. Overland, Michael Schirripa and Tom Wilderbuer
Fish population response to future climate drivers: A next step forward

Gordon H. Kruse, Jie Zheng and James E. Overland
A scenario approach to forecast potential impacts of climate change on red king crabs in the Eastern Bering Sea

Sukyung Kang, Jae Bong Lee, Anne B. Hollowed, Nicholas A. Bond and Suam Kim
Techniques for forecasting climate-induced variation in the distribution and abundance of mackerels in the northwestern Pacific

Michio J. Kishi, Yasunori Sakurai and Masahide Kaeriyama
What affects on the growth and stock of chum salmon, walleye pollack, and common squid in the Northern Pacific

Richard J. Beamish
A tail of two sockeyes

Richard J. Beamish
Evidence that the carrying capacity of local marine ecosystems can regulate the productivity of chinook salmon

Poster

Leonid Klyashtorin and Alexey Lyubushin
Cyclic climate changes and salmon production in the North Pacific

PICES Eighteenth Annual Meeting
October 23–November 1, 2009
Jeju, Republic of Korea

2009 Report of Working Group 20 on *Evaluations of Climate Change Predictions*

A Working Group 20 meeting was held in Jeju, Korea on October 25, 2009 from 14:00–18:00 hours. After introductory formalities by the Co-Chairmen, Drs. Michael Foreman (Canada) and Yasuhiro Yamanaki (Japan), and Dr. James Christian (Canada) agreeing to act as rapporteur, the meeting of participants (*WG 20 Endnote 1*) began according to the agenda (*WG 20 Endnote 2*) with a recap of the Terms of Reference (*WG 20 Endnote 3*).

AGENDA ITEM 3
Updates on work related to Terms of Reference

Dr. Foreman stated that the CFAME final report was nearing completion and had received input from WG 20 members Yasuhiro Yamanaka, Emanuele Di Lorenzo, Muyin Wang, Michael Foreman and Dr. Wang's collaborators, James Overland and Nicholas Bond. The report will include chapters, each on the California Current, Kuroshio/Oyashio, and Yellow/East China Seas ecosystems. It was also noted that WG 20's request for a one-year extension of its lifetime to collaborate with the new PICES/ICES Working Group on *Forecasting Climate Change Impacts on Fish and Shellfish* (WG-FCCIFS) was endorsed by Science Board.

AGENDA ITEM 4
Update on FUTURE and its new Advisory Panels

A discussion of FUTURE was moved to the top of the agenda, and Dr. Foreman gave a brief introduction to them and discussed outstanding issues about their structure and function. He gave a brief summary of the final version of the FUTURE Implementation Plan and the roles of its three new Advisory Panels. As Dr. Lorenzo was named a member of COVE (Advisory Panel on *Climate, Ocean Variaibility, and Ecosystems*) and POC members Drs. Steven Bograd, Shin-ichi Ito, Vyacheslav Labonov and Zhanggui Wang were named to AICE (Advisory Panel on *Anthropogenic Influences on Coastal Ecosystems*) and SOFE (Advisory Panel on *Status*, *Outlooks*, *Forecasts and Engagement*), it was felt that physical/geochemical oceanographic and climate issues would be well represented in FUTURE.

AGENDA ITEM 3, CONTINUED
Updates on work related to Terms of Reference

Brief updates on research progress relevant to the Terms of Reference were given by Drs. Elena Ustinova, Vadim Navrotsky, Enrique Curchitser, and Yamanaka, Christian, Lorenzo and Foreman. Dr. Muyin Wang had given an update of her work the preceding day in Workshop 8 on "*Exploring the predictability and mechanisms of Pacific low frequency variability beyond inter-annual time scales*". It was felt that these summaries demonstrated good progress against the first four Terms of Reference.

Dr. Foreman outlined the status of collaborations of WG 20 with WG-FCCIFS. They included his being named a Working Group member and his co-chairing (with Dr. Jason Holt of the Proudman Oceanographic Laboratory, Liverpool, UK) the Theme Session "*Downscaling variables from global models*" at the WG-FCCIFS workshop [later changed to an International Symposium] on "*Climate change Effects on Fish and Fisheries: Forecasting impacts, assessing ecosystem responses, and evaluating management strategies*" planned for Sendai, Japan in April 2010. Dr. Muyin Wang has agreed to give an invited presentation in this session. Given the relevance of both this session and another entitled "*Contemporary and next generation climate and oceanographic models,* *technical advances and new approaches*" to the WG 20 objectives, other Working Group members were encouraged to attend the Sendai workshop. An informal Working Group meeting might be convened there if there are enough members present.

AGENDA ITEM 5
WG 20 final report

Given that WG 20 will end after PICES-2010, discussions on the structure and content of its final report were initiated. The following rough outline of possible chapters was put forward:
1. Introduction, TOR, overview of progress and relevance to FUTURE,
2. Contributions to CFAME and WG-FCCIFS,
3. Wang/Overland/Bond: statistical downscaling in NEP, PDO representation,
4. Curchitser: dynamical downscaling,
5. Di Lorenzo and Miller: NPGO and ENSO representations and projections in GCMs, …
6. Foreman *et al.*: BC statistical and dynamical downscaling,
7. Yamanaka *et al.*: Kuroshio/Oyashio dynamical downscaling and ecosystem modeling,
8. Korean work?
9. Chinese work: Fan Wang will summarize various national efforts,
10. Russian work: Elena Ustinova and Vadim Navrotsky will contribute with help from Yury Zuenko,
11. Recommendations for FUTURE work.

Dr. Foreman agreed to send out emails in 1–2 months requesting more complete outlines of respective chapters from individual members. Though this report need not be finished by PICES-2010, it was agreed that there was no desire to continue much beyond that date.

AGENDA ITEMS 6 AND 7
Future WG 20 workshops/meetings

It was decided that WG 20 would propose a workshop entitled "PICES *Working Group on Evaluations of Climate Change (WG 20): Progress and FUTURE*" for PICES-2010. No invited speakers would be requested and presentations and discussions would concentrate on:
- progress related to the WG 20 Terms of Reference,
- status of, and future work on, the final report,
- follow-up activities that conform to FUTURE objectives and needs.

The possibility of submitting at least one oral presentation summarizing WG 20 activities to the Science Board Symposium at PICES-2010 was also discussed, and will be finalized via email as the deadline abstract submissions for that meeting comes closer.

AGENDA ITEM 8
Other business

No other business was discussed and the meeting was adjourned at about 17:30 hours.

WG 20 Endnote 1

WG 20 participation list

Members

James Christian (Canada)
Enrique Curshitser (U.S.A.)
Emanuele Di Lorenzo (U.S.A.)
Michael G. Foreman (Co-Chairman, Canada)
Arthur Miller (U.S.A.)
Vadim Navrotsky (Russia)
Elena Ustinova (Russia)
Fan Wang (China)
Muyin Wang (U.S.A.)
Yasuhiro Yamanaka (Co-Chairman, Japan)

Observers

Heui Chun An (Korea)
Stewart (Skip) McKinnell (PICES)
John E. Stein (PICES)
Yury Zuenko (Russia)

WG 20 Endnote 2

WG 20 meeting agenda

1. Welcome, introductions, opening remarks
2. Changes to, adoption of, agenda and appointment of rapporteur
3. Updates on work related to WG Terms of Reference
   a. Brief individual research summaries
   b. CFAME final report
   c. Collaboration with WG-FCCIFS: Sendai workshop, April 26–29, 2010
   d. Individual research summaries (Curchitser, *etc*.)
4. Update on FUTURE and its new Advisory Panels:
   a. Discussion on roles for WG20 & possible successor WG(s)
5. WG 20 final report:
   a. organization and content
   b. chapter assignments
6. Future WG 20 workshops/meetings
   a. Informal meeting at Sendai workshop?
   b. Final meeting and/or workshop/session at PICES 19, Portland, October 2010
   c. Other?
7. Items with financial implications
   a. Travel support requests
   b. Other items
8. Other business
9. Adoption of report for presentation at POC committee meeting

WG 20 Endnote 3

Terms of Reference

1. To analyze and evaluate climate change projections for the North Pacific and its marginal seas based on predictions from the latest global and regional models submitted to the Inter-governmental Panel on Climate Change (IPCC) for their 4th assessment report;
2. To facilitate analyses of climate effects on marine ecosystems and ecosystem feedbacks to climate by, for example computing an ensemble of the IPCC model projections for the North Pacific and making these projections available to other PICES groups such as CFAME;
3. To facilitate the development of higher-resolution regional ocean and coupled atmosphere-ocean models that are forced by, and take their boundary conditions from, IPCC global or regional models;
4. To facilitate the development of local and regional data sets (*e.g.*, SST, river flow, sea ice cover) incorporating information from climate model projections as well as observations and historical re-analyses;
5. To ensure effective two-way communication with CLIVAR;
6. To convene workshops/sessions to evaluate and compare results;
7. To publish a final report summarizing results.

PICES Eighteenth Annual Meeting Topic Session Summary

POC Workshop (W8)
Exploring the predictability and mechanisms of Pacific low frequency variability beyond inter-annual time scales

Co-Sponsored by CLIVAR

Co-Convenors: Emanuele Di Lorenzo (U.S.A.) and Shoshiro Minobe (Japan)

Understanding the dynamics that control climate variability in the Pacific basin is essential for exploring the degree of predictability of the ocean-atmosphere and sea-ice climate systems of the North Pacific. The goal of this workshop is to improve the conceptual and quantitative frameworks used by the PICES community to interpret low-frequency climate variability in the Pacific basin, ranging from interannual to multi-decadal timescales. Contributions are invited on a broad range of topics including: (1) studies that link regional to basin scale dynamics; (2) investigations of "regime shift", specifically the extent to which sharp transitions in the climate system are predictable and connected with low-frequency variations in the ocean-atmosphere and sea-ice systems; (3) studies that separate the stochastic and deterministic components of low-frequency climate fluctuations; (4) analysis of long-term observations collected in regional environments across the Pacific, specifically their relationship to large-scale climate processes as opposed to local-scale dynamics; (5) climate change and how it may impact the statistics of Pacific climate (*e.g.*, frequency of "regime shifts"); and (6) more generally studies that propose new mechanisms underlying low-frequency Pacific climate variability.

List of papers

Oral presentations

Topic 1: Pacific Large-scale dynamics and variability

Sumant Nigam and Bin Guan (Invited)
Ocean-atmosphere structure of Pacific decadal variability

Curtis Deutsch and Taka Ito (Invited)
Oxygen variability in the North Pacific

Sang-Wook Yeh, Yune-Jung Kang, Yign Noh and Arthur J. Miller
Characteristics in the North Pacific mean SST and its variability in climate transition periods

Skip McKinnell and Nate Mantua
Regimelettes – PDO variability in the 21st Century

Muyin Wang, James E. Overland and Nicholas A. Bond
A means for reducing projection uncertainty of climate models on regional scale

Topic 2: Tropical / Extratropical connections

Lixin Wu (Invited)
A unified teleconnection mechanism between extratropical and tropical oceans

Michael Alexander, Daniel J. Vimont, Ping Chang and James Scott (Invited)
The impact of extratropical atmospheric variability on the tropical Pacific: Testing the seasonal footprinting mechanism (W8-5648)

Daniel J. Vimont (Invited)
The role of thermodynamic coupling in connecting subtropical and tropical Pacific climate variations

Xiaohui Tang, Ping Chang and Fan Wang
Influence of reducing weather noise on ENSO prediction

Topic 3: Western North Pacific dynamics and variability

Bo Qiu, Shuiming Chen and Niklas Schneider (Invited)
Forced versus intrinsic variability of the Kuroshio Extension system on the decadal timescales

Shoshiro Minobe, Jiaxu Zhang and Miho Urasawa
Kuroshio Extension variability during the last 50-years and its predictability

Rong-shuo Cai, Qi-long Zhang and Hong-jian Tan
The long-term transport variation of Kuroshio and its adjacent currents in the western North Pacific Ocean

Masami Nonaka, Hisashi Nakamura, Bunmei Taguchi, Youichi Tanimoto and Hideharu Sasaki (Invited)
Decadal variability in the oceanic frontal zones in the western North Pacific Ocean

Elena I. Ustinova and Yury D. Sorokin
Low-frequency fluctuations of thermal conditions in the Far-Eastern Seas and large-scale climate processes

In-Seong Han, Young-Sang Suh, Jae-Dong Hwang and Joon-Soo Lee
Long-term change of thermal structure in the surface layer due to wind-induced conditions around the Korean Peninsula

Konstantin A. Rogachev and Natalia V. Shlyk
Surface freshening and mid-depth warming in the Pacific Western Subarctic since 1950s

Topic 4: Air Sea interaction and coupled structures

Bunmei Taguchi, Hisashi Nakamura, Masami Nonaka, Nobumasa Komori, Akira Kuwano-Yoshida, Hideharu Sasaki, Koutarou Takaya and Shang-Ping Xie (Invited)
Decadal variability of the Kuroshio/Oyashio Extension fronts and their atmospheric influences

Niklas Schneider, Yoshinori Sasaki, Axel Lauer, Bo Qiu, Arthur J. Miller and Detlef Stammer
Extratropical ocean to atmosphere coupling via atmospheric Ekman pumping (W8-5938)

Topic 5: Discussion/Synthesis

Emanuele Di Lorenzo, Niklas Schneider, Kim M. Cobb, Jason Furtado and Michael Alexander
ENSO and the North Pacific Gyre Oscillation: An integrated view of Pacific decadal dynamics

Arthur J. Miller, Emanuele Di Lorenzo, Shoshiro Minobe and Niklas Schneider
North Pacific decadal variability: Current understanding and unresolved issues

Posters

Rong-shuo Cai, Qi-long Zhang and Qing-hua Qi
Spatial and temporal oscillation and long-term variation in sea surface temperature field of the South China Sea

Yuri Nikonov
Description of seasonal water circulation variability in Tatar Strait in the Japan Sea by numerical method

Ling Ling Liu, Rui Xin Huang and Fan Wang
The role of diurnal cycle and mixed layer depth perturbations in ventilation: Subduction and obduction

Gennady V. Khen
Variability of the Kamchatka Current transport in the Kamchatka Strait

In-Seong Han, Takeshi Matsuno, Tomoharu Senjyu, Young-Sang Suh and Joon-Soo Lee
Behavior of low salinity water mass from Northern East China Sea to Korea Strait

PICES Nineteenth Annual Meeting
October 22–31, 2010
Portland, U.S.A.

2010 Report of Working Group 20 on *Evaluations of Climate Change Predictions*

The fifth and final meeting of Working Group on *Evaluations of Climate Change Projections* (WG 20) was held from 14:00–17:00 hours, October 24, 2010 in Portland, U.S.A. The Co-Chairman, Dr. Michael Foreman, called the meeting to order and, after introductory formalities, WG 20 member, Dr. Muyin Wang, kindly agreed to act as the rapporteur.

AGENDA ITEM 3
Review of Working Group Terms of Reference and summary of accomplishments

Dr. Foreman began the meeting with a recap of the WG 20 Terms of Reference (TORs) and a summary of activities addressing each one (*WG 20 Endnote 3*). It was generally felt that significant progress had been made with the IPCC GCM evaluations (#1), the development of regional climate models (RCMs) (#3), collaboration with other PICES expert groups like CFAME and WG 25 (#2), and convening PICES and international workshops/sessions (#5).

AGENDA ITEM 4
WG 20 final report

As WG 20 completed its tenure at this PICES meeting, a primary discussion point was the structure and content of the final report. It was agreed that each of the Working Group member chapters should summarize work accomplished *versus* the Terms of Reference and be 10–20 pages long. With an expectation of contributions from all Working Group members, the following chapter outline was put forward:

1) Acknowledgments, Abbreviations and Acronyms, Executive Summary,
2) Introduction: Background, Terms of Reference, Membership, Outline,
3) Wang, Overland, Bond: GCM downscaling procedures and examples,
4) Di Lorenzo, Miller: regional climate modeling and covariability in North Pacific,
5) Foreman and colleagues: RCM development for BC shelf waters,
6) Christian: GCM carbon cycle development,
7) Curchitser, Hermann: RCM development for the NE Pacific and Bering Sea and two-way coupling of this RCM into the NCAR GCM,
8) Ustinova, Zuenko: evaluation of climatic variability in Far Eastern Seas,
9) Navrotsky: interactions between climate and ecosystems,
10) Yamanaka, Hasumi, and colleagues: ecosystem projections for the Kuorshio/Oyashio system,
11) Jang, Pang, Yeh, Oh and colleagues: GCM projections of changes to mixed layer depth,
12) Qiao, Wang, Wu and colleagues: Chinese contributions,
13) Summary and recommendations.

It was emphasized that the final report is considered “grey literature” and will not be formally reviewed. As such, individual chapters should only give highlights of work that is either planned for publication, or has already been published. For specific PICES formatting requirements authors were referred to http://www.pices.int/publications/scientific_reports. The PICES Secretariat will technically edit the report and although MS Word files are preferred, other formats are acceptable (*e.g.*, LaTeX equations will be converted to MathType). Tables can either be in Word or Excel (no images of tables) and though the figures can be in any one of the common various formats (*e.g.*, eps, tiff, jpg), they should be good quality and use greyscale if colour is not necessary. Chapters should be sent to Dr. Foreman by December 31, 2010, with earlier submissions preferred.

As PICES Science Board and Governing Council are particularly interested in the recommendations from this Working Group, Dr. Foreman presented four possibilities (WG 20 Endnote 4) that will hopefully be expanded and extended in the final report. Draft Terms of Reference for a new working group on "North Pacific Climate Variability and Change" that was proposed by Drs. Emanuele Di Lorenzo and Shoshiro Minobe were also presented and discussed along with the four recommendations. Several comments were made asking for clarification of terminology (*e.g.*, conceptual mechanistic model), time scales, and scope, and these were recorded so they could be passed on to Drs. Di Lorenzo and Minobe. Possible membership (*e.g.*, the need to bring in new people) was also discussed.

AGENDA ITEM 5
Update on FUTURE and its Advisory Panels

Dr. Hiroaki Saito, Chairman of the FUTURE Advisory Panel on *Climate*, *Ocean Variaibility*, *and Ecosystems* (COVE-AP), gave a brief summary of its meeting on October 22. COVE-AP fully supports the proposed new "climate" working group and is proposing both another new working group on "Ecosystem Responses to Multiple Stressors " and a workshop on "*Indicators of status and change within North Pacific marine ecosystems: A FUTURE workshop*" to occur just before or after the inter-sessional Science Board meeting in April 2011.

AGENDA ITEM 6
Other business

Dr. Anne Hollowed gave a brief summary of recent activities of the joint PICES/ICES WG on *Forecasting Climate Change Impacts on Fish and Shellfish*. Though this Working Group ends in 2011, its high productivity has spawned discussion on how it will continue within each the ICES and PICES frameworks. Regardless of how the Group is re-structured, there will be an ongoing need for IPCC GCM and RCM projections so Dr. Hollowed was supportive of WG 20 recommendations on how that might be done.

No other business was discussed and the meeting was adjourned at 17:00. Dr. Foreman thanked all members for their contributions over the four-year tenure of the Working Group.

WG 20 Endnote 1

WG 20 participation list

Members

James Christian (Canada)
Enrique Curshitser (U.S.A.)
Michael Foreman (Co-Chairman, Canada)
Arthur Miller (U.S.A.)
Elena Ustinova (Russia)
Muyin Wang (U.S.A.)

Observers

Teresa A'mar (U.S.A.)
Kyung-Il Chang (Korea)
Anne Hollowed (U.S.A.)
Chan Joo Jang (Korea)
Dong-Jin Kang (Korea)
Jung Jin Kim (Korea)
Yuichiro Kumamoto (Japan)
Jae Hak Lee (Korea)
Tim Lee (U.S.A.)
Hanna Na (Korea)
Jae-Hyoung Park (Korea)
Thomas Royer (U.S.A.)
Toshi Saino (Japan)
Hiroaki Saito (Japan)
Sinjae Yoo (Korea)
Yury Zuenko (Russia)

WG 20 Endnote 2

WG 20 meeting agenda

1. Welcome, introductions, opening remarks
2. Changes to, adoption of, agenda and appointment of rapporteur
3. Review of WG Terms of Reference and summary of accomplishments
4. WG 20 final report:
   a. Organization, contents, formatting
   b. Chapter assignments and deadlines
   c. Recommendations for FUTURE
      i. TOR for a new WG
5. Update on FUTURE and its Advisory Panels (Hiroaki Saito)
6. Other business
7. Adoption of meeting report for presentation at POC committee meeting

WG 20 Endnote 3

Summary of WG 20 activities versus Terms of Reference

1. To analyze and evaluate climate change projections for the North Pacific and its marginal seas based on predictions from the latest global and regional models submitted to the Inter-governmental Panel on Climate Change (IPCC) for their 4th assessment report.
   - Several Wang/Overland/Bond papers published evaluating global climate models (GCMs) and their projections in North Pacific and Arctic,
   - Di Lorenzo, Miller and colleagues: condected NPGO analyses of IPCC model results,
   - Hasumi and colleagues continued analyses and improvements to Japanese GCM (MIROC),
   - Yamanaka and colleagues continued analyses of ecosystem models coupled to Japanese GCM,
   - Qiao and colleagues studied GCM improvements by addition of surface waves,
   - Ustinova and colleagues evaluated climate variability in Far Eastern seas,
   - Jang and colleagues studied GCM projected mixed layer depth changes in North Pacific,
   - Foreman and colleagues evaluated GCM winds off BC.

2. To facilitate analyses of climate effects on marine ecosystems and ecosystem feedbacks to climate by, for example computing an ensemble of the IPCC model projections for the North Pacific and making these projections available to other PICES groups such as CFAME.
   - Worked with CFAME,
     – Conducted joint workshops at PICES Annual Meetings, and April 2008 workshop in Hawaii,
     – Contributed to the final report and co-authored publication,
   - Working with WG25 – joint PICES/ICES WG-FCCIFS,
     – Foreman, Yamanaka are WG 25 members,
     – Co-convened Theme Session on "*Downscaling variables from global models*" in which WG 20 members participated in, at the International Symposium on "*Climate change effects on fish and fisheries: Forecasting impacts, assessing ecosystem responses, and evaluating management strategies*", April 2010 in Sendai, Japan,
     – Manuscripts were submitted to ICES Journal of Marine Science
   - Yamanaka and colleagues continued development and analyses of an ecosystem model coupled to Japanese GCM

3. To facilitate the development of higher-resolution regional ocean and coupled atmosphere–ocean models that are forced by, and take their boundary conditions from, IPCC global or regional models.
   - RCMs developed, or under development, for:
     – California shelf (Auad, Miller, Di Lorenzo),
     – NE Pacific and Bering Sea – fully coupled to NCAR GCM (Curchitser *et al.*),
     – BC shelf (Foreman *et al.*),
     – Washington-Oregon shelf (Bond, Hermann, Curchitser),

- – Kuroshio region (Kurogi, Hasumi, Tanaka),
- Curchitser participated in RCM workshop in September,
- Japanese have 0.25° resolution GCM.

4. To facilitate the development of local and regional data sets (*e.g.*, SST, river flow, sea ice cover) incorporating information from climate model projections as well as observations and historical re-analyses.
   - Augmenting a data set of buoy wind measurements off the BC coast by filling gaps over the last decade with values from a NASA archive and analysing 50-year time series for trends in magnitude or timing,
   - Argo float data freely available (Freeland has given several summaries at POC meetings),
   - See recommendation #3.

5. To ensure effective two-way communication with CLIVAR.
   - CLIVAR representatives gave presentations at WG 20 business meetings or co-sponsored workshops at several PICES Annual Meetings,
   - A close relationship has been maintained with ESSAS (Wang, Curchitser).

6. To convene workshops/sessions to evaluate and compare results.
   - Conducted annual workshops at all PICES meetings,
     - 3 jointly with CFAME,
   - Participated in the CFAME inter-sessional workshop on "*Linking and visualizing climate-forcing mechanisms and marine ecosystem changes: A comparative approach*" in Honolulu, April 2008,
   - Co-convened a Theme Session on "*Climate model projections*" at the International Symposium on "*Effects of climate change in the World's oceans*", May 2008 in Gijón, Spain,
   - Co-convened a Theme Session on "*Downscaling variables from global models*" at the International Symposium on "*Climate change Effects on Fish and Fisheries: Forecasting impacts, assessing ecosystem responses, and evaluating management strategies*", April 2010 in Sendai, Japan.

7. To publish a final report summarizing results.
   - Proceeding.

WG 20 Endnote 4

Draft recommendations for the final report

1. Continue evaluating IPCC GCM (and RCM) results.
   a. James Overland, Muyin Wang, Chan Joo Jang (and others?) plan evaluations of new AR5 outputs when they are available (winter 2010–11?);
   b. WG 25 (joint PICES/ICES Working Group on *Forecasting Climate Change Impacts on Fish and Shellfish*) will be interested in these forecasts;
   c. The RCM community is hoping to have a chapter in AR5;
   d. Besides continuing Japanese GCM/ecosystem model studies (Yamanaka and colleagues), several North Pacific RCMs are under development that are being, or could be, coupled to ecosystem models (*e.g.*, Curchitser, Hermann, Rose *et al.*);
   e. This activity may not warrant a new Working Group but the work should be part of COVE-AP and/or SOFE-AP.

2. Continue analyses of North Pacific inter-annual to inter-decadal variability. This would be an extension of the PICES-2009 workshop on "*Exploring the predictability and mechanisms of Pacific low frequency variability beyond inter-annual time scales*" (W8) convened by Emanuele Di Lorenzo and Shoshiro Minobe.
   - A new working group, under POC and with COVE-AP's support, has been proposed (*WG 20 Endnote 5* has the draft Terms of Reference);
   - IPCC-AR5 will include decadal predictions. Unlike GCM predictions that should only be evaluated statistically, these decadal predictions should be directly comparable with subsequent observations. An analysis of these predictions could be part of SOFE.

3. Establish live-access servers or ftp sites to archive and provide easy access to results from RCMs, analogous to the PCMDI archive for IPCC GCM results.
   - This would address WG 20 TOR #4, something that was not adequately accomplished during the tenure of the Working Group;
   - It would also provide fisheries scientists (*e.g.*, WG-FCCIFS) with climate change variables on much finer spatial scales than can be resolved with the GCMs.
   - This could be a possible activity for the COVE or SOFE Advisory Panels and TCODE.

4. Provide and regularly update lists of links to GCM/RCM sites like NARCCAP (North American regional climate model results, http://www.narccap.ucar.edu/) and to relevant publications like the "Guide to Best Practices on the Use of Climate Models" (Overland *et al.*).

WG 20 Endnote 5

Proposal for a new Working Group on "North Pacific Climate Variability and Change"

Motivation

The need to develop essential mechanistic understandings of North Pacific climate variability and change that can better guide the formulation of process-based hypotheses underlying the links between ecosystem dynamics and physical climate.

Draft Terms of Reference

1. Develop conceptual mechanistic models or frameworks of North Pacific climate variability and change that can be readily used by ecosystem scientists to explore hypotheses of the links between ecosystem dynamics and physical climate.
2. Summarize the current understanding of mechanisms of Pacific climate variability, and evaluate the strengths of the underlying hypotheses with supporting evidence.
3. Coordinate, in conjunction with ecosystem scientists, the development and implementation of process-based models to hindcast the variability of available long-term biological time series.
4. Provide improved metrics to test the dynamics of the IPCC models.
5. Understand and fill the gaps between what the physical models can currently produce and what ecosystem scientists suggest are important physical forcing factors required for predicting species and ecosystem responses to climate change.
6. Maintain linkages with, and summarize the results from National and International programs/projects such as CLIVAR, IMBER, US CAMEO, ESSAS, Japanese Hot Spot in the Climate System, POMAL, CREAMS EAST-I, POBEX, and others.
7. Convene workshops and sessions to evaluate and compare results.
8. Publish a final report summarizing results.

Suggested Co-Chairmen*:* E. Di Lorenzo (U.S.A.), S. Minobe (Japan), M. Foreman (Canada)

PICES Nineteenth Annual Meeting Topic Session Summary

POC Workshop (W4)
PICES Working Group on Evaluations of Climate Change Projections (WG 20): Progress and FUTURE

Co-Convenors: *Michael G. Foreman (Canada) and Yasuhiro Yamanaka (Japan)*

Summary of Business Meeting and Discussions

After introductory formalities and Muyin Wang kindly agreeing to act as the rapporteur, Mike began the meeting began with a recap of the WG Terms of Reference (TORs) and his personal summary (Appendix 1) of activities addressing each one. It was generally felt that significant progress had been made with the IPCC GCM evaluations (#1), the development of regional climate models (RCMs) (#3), collaboration with other PICES groups like CFAME and WG25 (#2), and convening PICES and international workshops/sessions (#5).

As WG20 completed its tenure at this PICES meeting, a primary discussion point was the structure and content of the final report. It was agreed that each of the WG member chapters should summarize work accomplished versus the TORs and be 10-20 pages long. With an expectation of contributions from all members, the following chapter outline was put forward:

1) Acknowledgments, Abbreviations & Acronyms, Executive Summary
2) Introduction: background, Terms of Reference, membership, outline
3) Wang, Overland, Bond: GCM downscaling procedures & examples
4) Di Lorenzo, Miller: regional climate modeling & covariability in North Pacific
5) Foreman & colleagues: RCM development for BC shelf waters
6) Christian: GCM carbon cycle development
7) Curchitser, Hermann: RCM development for the NE Pacific and Bering Sea & two-way coupling of this RCM into the NCAR GCM
8) Ustinova, Zuenko: evaluation of climatic variability in Far Eastern Seas
9) Navrotsky: interactions between climate and ecosystems
10) Yamanaka, Hasumi, & colleagues: ecosystem projections for the Kuorshio/Oyashio system
11) Jang, Pang, Yeh, Oh & colleagues: GCM projections of changes to mixed layer depth
12) Qiao, Wang, Wu & colleagues: Chinese contributions
13) Summary and recommendations

It was emphasized that the final report is considered "grey literature" and will not be formally reviewed. As such, individual chapters should only give highlights of work that is either planned for publication, or has already been published. For specific PICES formatting requirements authors were referred to http://www.pices.int/ publications/scientific_reports. Rosalie Rutka from the PICES Secretariat will be the technical editor and although she prefers MS Word files, she will accept other formats (*e.g.*, LaTEX equations will be converted to MathType). Tables can either be in Word or Excel (no images of tables) and though the figures can be in any one of the common various formats (*e.g.*, eps, tiff, jpg), they should be good quality and use greyscale if colour is not necessary. Tables and figures can be put at the end of each chapter and Rosalie will fit them into the text later. Chapters should be sent to Mike by December 31, 2010, with earlier submissions preferred.

As PICES Science Board and Governing Council are particularly interested in the recommendations from this WG, Mike presented four possibilities (Appendix 2) that will hopefully be expanded and extended in the final report. Draft TORs for a new working group on "North Pacific Climate Variability and Change" that was proposed by Emanuele Di Lorenzo and Shoshiro Minobe were also presented and discussed along with the four recommendations. Several comments were made asking for clarification of terminology (*e.g.*, conceptual mechanistic model), time scales, and scope, and these were recorded so they could be passed on to Di Lorenzo and Minobe. Possible membership (*e.g.*, the need to bring in new people) was also discussed.

Hiroaki Saito, chair of the COVE Advisory Panel, gave a brief summary of the COVE meeting on October 22. COVE fully supports the proposed new "climate" working group and is proposing both another new working group on “Ecosystem Responses to Multiple Stressors “ and a workshop on “Indicators of Status and Change within North Pacific Marine Ecosystems: a FUTURE workshop” to occur just before or after the Inter-sessional Science Board meeting in April.

Anne Hollowed gave a brief summary of recent activities of the ICES/PICES joint WG on Forecasting Climate Change Impacts on Fish and Shellfish. Though this WG ends in 2011, their high productivity has spawned discussion on how it will continue within each the ICES and PICES frameworks. Regardless of how the group is re-structured, there will be an ongoing need for IPCC GCM and RCM projections so Anne was supportive of WG20 recommendations on how that might be done.

No other business was discussed and the meeting was adjourned at about 5:00pm. Mike thanked all members for their contributions over the four year tenure of the working group.

Meeting Agenda

1. Welcome, introductions, opening remarks
2. Changes to, adoption of, agenda and appointment of rapporteur
3. Update on FUTURE & its Advisory Panels (Hiroaki Saito)
4. Review of WG Terms of Reference & summary of accomplishments
5. WG20 Final Report:
    a. Organization, contents, formatting
    b. Chapter assignments & deadlines
    c. Recommendations for FUTURE
        i. TOR for a new WG
6. Other business
7. Adoption of meeting report for presentation at POC committee meeting

Attendees

WG20 Members
Mike Foreman (Canada)
Jim Christian (Canada)
Elena Ustinova (Russia)
Enrique Curshitser (USA)
Muyin Wang (USA)
Art Miller (USA)

Observers
Kyung-Il Chang (Korea)
Jae-Hyoung Park (Korea)
Teresa A’mar (USA)
Tim Lee (USA)
JungJin Kim (Korea)
Hanna Na (Korea)
Tom Royer (USA)
Jae Hak Lee (Korea)
Anne Hollowed (USA)
Yury Zuenko (Russia)
Chan Joo Jang (Korea)
Sinjae Yoo (Korea)
Dong-Jin Kang (Korea)
Toshi Saino (Japan)
Yuichiro Kumamoto (Japan)
Hiroaki Saito (Japan)

Appendix 1: Summary of WG 20 Activities versus Terms of Reference

a. To analyze and evaluate climate change projections for the North Pacific and its marginal seas based on predictions from the latest global and regional models submitted to the Inter-governmental Panel on Climate Change (IPCC) for their 4th assessment report
   - Several Wang/Overland/Bond publications evaluating global climate models (GCMs) & their projections in North Pacific & Arctic
   - Di Lorenzo, Miller & colleagues: NPGO analyses of IPCC model results
   - Hasumi & colleagues continued analyses & improvements to Japanese GCM (MIROC)
   - Yamanaka & colleagues continued analyses of ecosystem models coupled to Japanese GCM
   - Qiao & colleagues studied GCM improvements by addition of surface waves
   - Ustinova & colleagues evaluated climate variability in Far Eastern seas
   - Jang & colleagues studied GCM projected mixed layer depth changes in North Pacific
   - Foreman & colleagues evaluated GCM winds off BC

b. To facilitate analyses of climate effects on marine ecosystems and ecosystem feedbacks to climate by, for example computing an ensemble of the IPCC model projections for the North Pacific and making these projections available to other PICES groups such as CFAME
   - Worked with CFAME
     - Joint workshops at PICES annual meetings & April 2008 workshop in Hawaii
     - Contributed to final report & co-authored publication
   - Working with WG25 – ICES/PICES WGCCIFS
     - Foreman, Yamanaka are WG25 members
     - Co-convened downscaling session at, & members participated in, Sendai symposium
     - Manuscripts submitted to ICES J Mar Sci
   - Yamanaka & colleagues continued development & analyses of ecosystem model coupled to Japanese GCM

c. To facilitate the development of higher-resolution regional ocean and coupled atmosphere-ocean models that are forced by, and take their boundary conditions from, IPCC global or regional models
   - RCMs developed, or under development, for
     - California shelf (Auad, Miller, Di Lorenzo)
     - NE Pacific & Bering Sea – fully coupled to NCAR GCM (Curchitser et al.)
     - BC shelf (Foreman *et al*.)
     - Washington-Oregon shelf (Bond, Hermann, Curchitser)
     - Kuroshio region (Kurogi, Hasumi, Tanaka)
   - Curchitser participated in RCM workshop in September
   - Japanese have 0.25° resolution GCM

d. To facilitate the development of local and regional data sets (*e.g.*, SST, river flow, sea ice cover) incorporating information from climate model projections as well as observations and historical re-analyses
   - Augmenting a data set of buoy wind measurements off the BC coast by filling gaps over the last decade with values from a NASA archive & analysing 50 year time series for trends in magnitude or timing
   - Argo float data freely available (Freeland has given several summaries at POC meetings)
   - See recommendation #3

e. To ensure effective two-way communication with CLIVAR
   - CLIVAR representatives gave presentations at several WG20 annual meetings
   - Close relationship with ESSAS (Wang, Curchitser)

f. To convene workshops/sessions to evaluate and compare results
   - Annual workshops at all PICES meetings , 3 jointly with CFAME
   - Participated in CFAME workshop, Honolulu, April 2008
   - Co-convened downscaling session at “Effects of Climate Change in the World’s Oceans”, Gijón, May 2008

- Co-convened downscaling session at "Climate Change Effects on Fish and Fisheries", Sendai, April 2010

g. To publish a final report summarizing results.
   - Proceeding

Appendix 2: Draft Recommendations for the Final Report

1) Continue evaluating IPCC GCM (and RCM) results:
   a. Jim Overland, Muyin Wang, Chan Joo Jang (and others?) plan evaluations of new AR5 outputs when they are available (winter 2010-11?)
   b. WG25 (Forecasting Climate Change Impacts on Fish and Shellfish) will be interested in these forecasts
   c. The RCM community is hoping to have a chapter in AR5
   d. Besides continuing Japanese GCM/ecosystem model studies (Yamanaka and colleagues), several North Pacific RCMs are under development that are being, or could be, coupled to ecosystem models (*e.g.*, Curchitser, Hermann, Rose *et al*.)
   e. This activity may not warrant a new WG but the work should be part of COVE and/or SOFE
2) Continue analyses of North Pacific inter-annual to inter-decadal variability. This would be an extension of the PICES 2009 workshop convened by Di Lorenzo and Minobe.
   - A new WG, under POC and with COVE's support, has been proposed (Appendix 3 has draft TORs)
   - IPCC-AR5 will include decadal predictions. Unlike GCM predictions that should only be evaluated statistically, these decadal predictions should be directly comparable with subsequent observations. An analysis of these predictions could be part of SOFE.
3) Establish live-access servers or ftp sites to archive and provide easy access to results from RCMs, analogous to the PCMDI archive for IPCC GCM results.
   - This would address WG20 TOR #4, something that was not adequately accomplished during the tenure of that WG
   - It would also provide fisheries scientists (*e.g.*, WG-FCCIFS) with climate change variables on much finer spatial scales than can be resolved with the GCMs.
   - This could be a possible activity for the COVE or SOFE Advisory Panels and the TCODE Committee.
4) Provide and regularly update lists of links to GCM/RCM sites like NARCCAP (North American regional climate model results, http://www.narccap.ucar.edu/) and to relevant publications like the "Guide to Best Practices on the Use of Climate Models" (Overland *et al.*)

Appendix 3: Proposal for a new Working Group: "North Pacific Climate Variability and Change"

Motivation:
Need to develop essential mechanistic understandings of North Pacific climate variability & change that can better guide the formulation of process-based hypotheses underlying the links between ecosystem dynamics and physical climate.

Draft Terms of Reference:
1. Develop conceptual mechanistic models or frameworks of North Pacific climate variability & change that can be readily used by ecosystem scientists to explore hypotheses of the links between ecosystem dynamics and physical climate.
2. Summarize the current understanding of mechanisms of Pacific climate variability, and evaluate the strengths of the underlying hypotheses with supporting evidence.
3. Coordinate, in conjunction with ecosystem scientists, the development & implementation of process-based models to hindcast the variability of available long-term biological time series.
4. Provide improved metrics to test the dynamics of the IPCC models.
5. Understand and fill the gaps between what the physical models can currently produce and what ecosystem scientists suggest are important physical forcing factors required for predicting species and ecosystem responses to climate change.

6. Maintain linkages with, and summarize the results from National & International programs/projects such as CLIVAR, IMBER, US CAMEO, ESSAS, Japanese Hot Spot in the Climate System, POMAL, CREAMS EAST-I, POBEX, and others.
7. Convene workshops & sessions to evaluate and compare results
8. Publish a final report summarizing results.

Possible Co-Chairs: E. Di Lorenzo (USA), S. Minobe (Japan), M. Foreman (Canada)

Objectives

Present and discuss drafts of chapters for the final WG20 Report and finalize recommendations to PICES/FUTURE. The following list of possible chapters was put forward at the April WG20 meeting in Sendai, Japan:

- Introduction: Background and Terms of Reference
- Wang, Overland, Bond: GCM downscaling procedures & examples
- Di Lorenzo, Miller: Regional climate modeling and covariability in North Pacific
- Foreman and colleagues: RCM development for BC shelf waters
- Christian: GCM carbon cycle development
- Curchitser, Hermann: RCM development for the NE Pacific and Bering Sea and two-way coupling of this RCM into the NCAR GCM
- Ustinova, Zuenko: Evaluation of climatic variability in Far Eastern Seas
- Navrotsky: Interactions between climate and ecosystems
- Yamanaka, Hasumi, and colleagues: Ecosystem projections for the Kuorshio/Oyashio system
- Jang, Pang, Park, Yeh, and colleagues: GCM projections of changes to mixed layer depth
- Qiao, Wang, Wu and colleagues: Chinese contributions

Informal Agenda:
1. Review of WG20 Terms of Reference and what was accomplished
2. Discussion of proposed chapter topics and presentations of recent research that might be included
3. Updates on chapter assignments and setting of deadlines
4. Recommendations for follow-up work and/or groups within FUTURE Summary of Seoul Advisory Panel meeting, August 16-18
5. Adjournment to local pub/restaurant

Appendix 6

PICES Press Articles

2008 PICES Workshop on "*Climate Scenarios for Ecosystem Modeling (II)*"

by Michael Foreman, Anne Hollowed and Suam Kim

A key component of FUTURE (an acronym for Forecasting and Understanding Trends, Uncertainty and Responses of North Pacific Marine Ecosystems), the new over-arching science program within PICES, is understanding and communicating the impacts of climate change on North Pacific marine ecosystems. Whereas FUTURE's predecessor, the Climate Change and Carrying Capacity (CCCC) Program, focussed primarily on past climate change effects, this new program will have a stronger emphasis on future changes, and thus rely heavily on the global climate model projections described in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Toward that end, the CFAME (*Climate Forcing and Marine Ecosystems*) Task Team of the CCCC Program has laid some of the groundwork for FUTURE by collaborating with the Working Group on *Evaluations of Climate Change Projections* (WG 20) in analysing downscaled atmospheric and physical oceanographic projected changes from a suite of global climate models to determine their impact on states of three North Pacific ecosystems: the California Current System, the Kuroshio/Oyashio System, and the Yellow and East China Seas System (see PICES Press, Vol. 16, No. 2, for the summary of their April 2008 workshop). A joint workshop of these two groups on "*Climate scenarios for ecosystem modeling (I)*" took place at the 2007 PICES Annual Meeting in Victoria, Canada, and a follow-up 1.5-day workshop, jointly organized by CFAME, WG 20, and a prospective new ICES/PICES Working Group on *Forecasting Climate Change Impacts on Fish and Shellfish*, was held at the 2008 PICES Annual Meeting in Dalian, China. This article summarizes some highlights of this second workshop that was co-convened by Michael Foreman, Anne Hollowed, Suam Kim, and Gordon McFarlane.

The workshop opened with an invited presentation by Thomas Okey (Pew Fellow in Marine Conservation) on the challenge of forecasting changes to marine biota and fisheries in the year 2035. He summarized discussions from, and collaborations established at, a workshop preceding the conference on "*The Effects of climate change on the world's oceans*" held in Gijón, Spain, in May 2008, and outlined the motivation for the new ICES/PICES Working Group that is being led by Anne Hollowed. The next two speakers, James Overland and Young-Shil Kang gave updates of their work relevant to the CFAME terms of reference. In particular, Jim stressed that among the 22 global climate models that he and his colleagues Muyin Wang and Nicholas Bond investigated, no one model was uniformly best in capturing all the important oceanic features in the North Pacific. However, he did show a "wall of fame/shame" table rating model relative performance and indicated a group of approximately six models that gave generally acceptable results over a standard evaluation period, and that should be used in future ensemble estimates of climate change in the North Pacific.

Five out of the next six presentations were progress updates given by WG 20 members. Yasuhiro Yamanaka described recent results received with the COCO-NEMURO coupled biophysical climate model for the Kuroshio/Oyashio region. Emanuele Di Lorenzo gave a preview of his subsequent award-winning Science Board presentation describing his North Pacific Gyre Oscillation (NPGO) analysis of variability in North Pacific sea surface elevations and its links with ENSO signals. Jim Christian described the development of a carbon cycle component within the next generation of the Canadian Global Climate Model. Enrique Curchitser showed preliminary results of improved upwelling arising from embedding and fully coupling his 10-km regional ROMS model for the Northeast Pacific within the NCAR global climate model. Michael Foreman described wind downscaling results and new regional climate and ecosystem model initiatives in Canadian waters. Within these updates, Qigeng Zhao described his simulations of acidification in the Pacific.

The remaining presentations provided information on efforts to forecast the implications of climate change on fish and shellfish in the North Pacific. Anne Hollowed discussed a framework for making forecasts by using statistical methods to select credible IPCC models and extract their expected forcing. This forcing could then be incorporated into statistical age-structured models to project impacts on commercial fish populations. Gordon Kruse presented a qualitative method that could be used to forecast climate change impacts on red king crab stocks in the Eastern Bering Sea. Suam Kim talked about the response of Korean chub mackerel populations to climate forcing, showing that salinity is significantly correlated to year-class strength and suggesting that shifts in transport may play a key role in recruitment variability of this stock. Michio Kishi examined the role of climate variability on the growth of salmon, pollock and squid in the northwestern Pacific using a bio-energetic model. Preliminary results of this study suggest that chum salmon may not survive in waters off Hokkaido in 2100. Richard Beamish gave two talks on the impact of climate change on salmon stocks in British Columbia. His first talk showed that poor marine survivial of chinook salmon in the Strait of Georgia appears to be related to reduced growth resulting from a declining carrying capacity in the area, while his second talk compared two sockeye salmon runs that exhibited different population trends. As was the case in the first talk, the different trends appear to be related to the spatial distribution of food and the behaviour of juvenile salmon.

The final half-day of the workshop was devoted to discussions on the proposed new ICES/PICES Working Group on *Forecasting Climate Change Impacts on Fish and Shellfish* (WGFCCIFS). Manuel Barange, one of the ICES Co-Chairs for this group, provided an overview of

ICES-community interest in this effort and noted that ICES had already approved the formation of WGFCCIFS and its terms of reference. Individuals from PICES member countries identified several research programs that would contribute to the activities of the working group.

The participants discussed the rationale for start and end dates of 2035 and 2100, respectively, for the investigations. The former date was selected because it is the projected time when the climate change signal will begin to overwhelm the interannual and interdecadal signal in the North Pacific. The end date was selected because after it, forecasts will be heavily dependent on which particular IPCC emission scenario is chosen for predicting the rate of greenhouse gas build-up in the atmosphere. Mikhail Stepanenko noted that managers are most interested in forecasting future fish populations over short time horizons, and therefore, we should not ignore any efforts to also improve short-term projections. A clear linkage between short-term and long-term projections will be model validation activities. By examining the performance of projections in the short-term, analysts should be able to quantify expected inaccuracies associated with the long-term projections.

Different frameworks for delivering IPCC model output were discussed. It was agreed that the ideal framework would be one where oceanographers and climatologists from each member nation work with their biologists and modellers to develop relevant forecasts. However, it was noted that James Overland, Muyin Wang, and Nicholas Bond from the Pacific Marine Environmental Laboratory would be willing to assist various groups, when necessary and as time permits.

The participants had a lively discussion of the topic of communicating uncertainty. George Sugihara mentioned that forecasting is a complicated science and that there is a variety of analytical tools that have been developed for the business community which could be applied here. Jake Rice noted that the issue of communicating uncertainty requires that we identify the stakeholders who might be interested in our forecasts. It was noted that the advice of PICES and ICES on the future status of marine resources around the world could be used to address the following issues:

- global food security;
- implications on northward shifts in stocks on managing domestic fisheries, including shifts in the locations of fishes (*e.g.*, sardines, hake) and rights-based (communities and businesses) solutions;
- new fisheries in the north (especially for Canada, Russia and U.S.A.);
- assessing species and populations at risk (what are appropriate recovery targets for species in a changing world?).

Patricio Bernal (Intergovernmental Oceanographic Commission of UNESCO) indicated that his organization would be very interested in this new ICES/PICES effort. It was agreed that potential collaborations with IOC, FAO and other organizations would be investigated.

Dr. Michael Foreman (mike.foreman@dfo-mpo.gc.ca) is a physical oceanographer and numerical modeller for Fisheries and Oceans Canada at the Institute of Ocean Sciences in Sidney, British Columbia. His research interests include coastal circulation and river modelling, biological transport, tidal analysis, and climate change. Within PICES, he has been Chairman of the Physical Oceanography and Climate Committee since 2005, and Co-Chairman of Working Group 20 on Evaluations of Climate Change Projections *since 2006.*

Dr. Anne Hollowed (anne.hollowed@noaa.gov) is a Senior Scientist at the NOAA's Alaska Fisheries Science Center, in Seattle, U.S.A. She holds a M.S. in Oceanography from Old Dominion University, and a Ph.D. in Fisheries from the University of Washington. She is an Affiliate Associate Professor at the University of Washington and a Fellow of the Cooperative Institute for Arctic Research at the University of Alaska. Anne has served on panels for U.S. GLOBEC, PICES CCCC, the North Pacific Research Board, and Comparative Analysis of Marine Ecosystem Organization, and is a member of the Scientific and Statistical Committee of the North Pacific Fisheries Management Council.

Dr. Suam Kim (suamkim@pknu.ac.kr) received his B.Sc. (1976) and M.Sc. (1979) from the Seoul National University and his Ph.D. in Fisheries Oceanography from the University of Washington in 1987. Currently, he is a Professor of the Pukyong National University, Busan, Korea. His areas of interest include fisheries ecology, especially recruitment variability focusing on early life histories of fish in relation to oceanic/climate changes. Suam represented Korea on several international organizations/programs such as PICES, GLOBEC, CCAMLR, IGBP, NPAFC and SCAR. Currently, he serves as President of NPAFC.

2009 Mechanism of North Pacific Low Frequency Variability Workshop

by Emanuele Di Lorenzo and Shoshiro Minobe

A 2-day workshop on "*Exploring the predictability and mechanisms of Pacific low frequency variability beyond inter-annual time scales*", co-convened by the authors of this article, was held on October 24–25 at the 2009 PICES Annual Meeting in Jeju, Korea. The workshop was well attended with over 25 contributors, and was divided into four sections: (1) *Ocean and atmosphere variability in the North Pacific*, (2) *Coupling between tropics and extra-tropics*, (3) *North Pacific western boundary variability and feedbacks*, and (4) *Discussion and synthesis*. Thanks to the support of PICES, we were able to accommodate eight invited speakers, who covered each of the focus areas: Sumant Nigam (University of Maryland, U.S.A.), Curtis Deutsch (University of California Los Angeles, U.S.A.), Lixin Wu (Open University of China) Michael Alexander (NOAA, U.S.A.), Dan Vimont (University of Wisconsin-Madison, U.S.A.), Bo Qiu (University of Hawaii, U.S.A.), Masami Nonaka and Bunmei Taguchi (Earth Simulator, JAMSTEC, Japan). The overall goal of this workshop was to review our current understanding of the dynamics underlying low-frequency fluctuations of the Pacific and to isolate potential mechanisms and linkages (*e.g.*, tropics/ extra-tropics coupling, ocean/atmosphere coupling/feedbacks in the western boundary current system) that can provide the basis for low-frequency predictability.

Ocean and atmosphere variability in the North Pacific

(Invited speakers: S. Nigam and C. Deutsch)

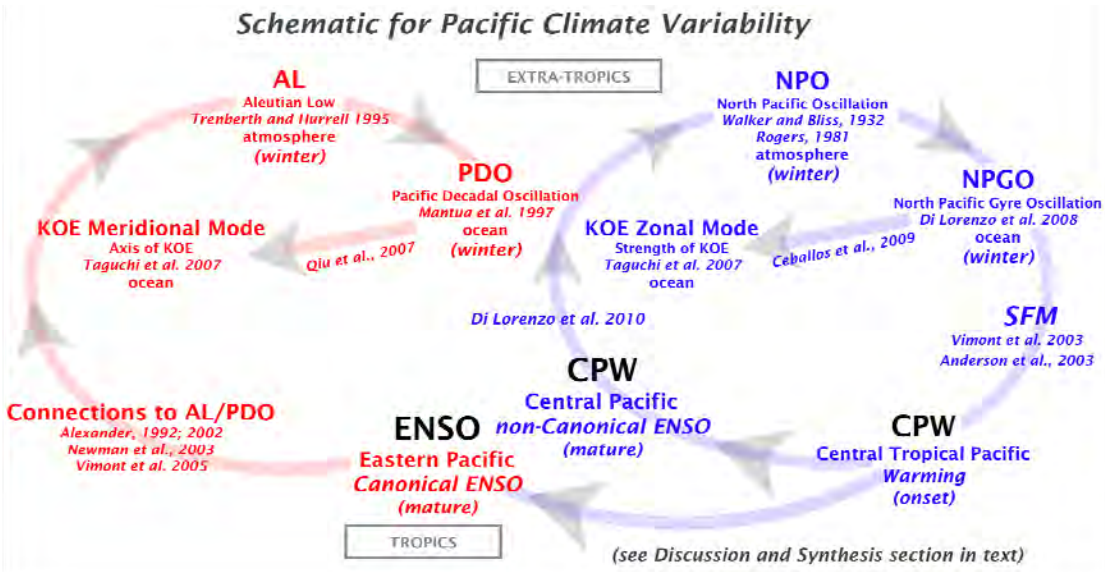
The first section of the workshop was devoted to review of our current understanding of the modes of ocean low-frequency variability that act on timescales beyond interannual, and of the relationship between modes of variability in the ocean and atmosphere (*S. Nigam*). Several talks focused on the importance of the first two dominant modes of sea surface temperature (SST) and sea surface height (SSH) variability of the North Pacific, namely the Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO). Strong climate transitions of the North Pacific are likely better understood by considering both modes. For example, while the PDO has played a dominant role in the 1976–77 climate transition, the NPGO dominated the 1988–89 climate transition (*S. Yeh*). These transitions are a prominent signal in marine ecosystems and in biogeochemical tracers (*e.g.*, oxygen), although the dynamics connecting physics to ecosystems and biogeochemistry was not explored and to large extent remains unclear (*C. Deutsch*). While it was suggested that part of the Pacific low-frequency variability may be forced by the Lunar and Solar cycle (*e.g.*, PDO, *S. McKinnell*), it was generally recognized that the dynamics of the oceanic modes can be understood in the context of their atmospheric drivers. While the PDO responds to variability of the Aleutian Low (AL) (*S. Nigam*), the NPGO appears to be forced by the North Pacific Oscillation (NPO) (*E. Di Lorenzo*), which emerges as the second dominant pattern of North Pacific sea level pressure after the AL. The AL and NPO are the surface expressions of atmospheric variability associated with the Pacific North American (PNA) and Western Pacific (WP) teleconnection patterns. Statistical analysis of SST (*S. Nigam*) also isolated a Pan-Pacific decadal variability mode that is related to the Atlantic Multidecadal Oscillation (AMO), which needs further investigation in terms of ecosystem impacts and may provide means to synchronize ecosystem variations between oceanic basins (*e.g.*, Atlantic and Pacific). Understanding how modes of ocean and atmospheric variability such as the PNA/AL/PDO and WP/NPO/NPGO respond to anthropogenic climate forcing was also discussed and remains an outstanding issue (*M. Wang*).

Coupling between tropics and extra-tropics

(Invited speakers: L. Wu, M. Alexander and D. Vimont)

This section of the workshop explored the mechanisms and dynamics by which tropics and extra-tropics interact. While we have known for a while that tropical activity associated with the canonical El Niño Southern Oscillation (ENSO) excites atmospheric variability of the PNA/AL/PDO, recent studies (*D. Vimont, M. Alexander*) also suggest that the extra-tropical variability of the NPO/NPGO – the second dominant pattern of atmospheric/ocean variability in the North Pacific – can affect ENSO. Coupled ocean/atmosphere model experiments shown by *D. Vimont* suggest that the NPO variability in the North Pacific excites a mode of variability that is independent of ENSO. This mode – referred to as the Meridional Mode because of its north-south spatial and temporal structure – generates warm temperature anomalies in the central tropical Pacific that lead to an ENSO response about one year later. Support for this hypothesis was presented using coupled climate models (*M. Alexander*). In addition to the NPO/NPGO to ENSO connection, other studies that used partial coupling of a coupled climate model suggested that the PNA/ AL/PDO North Pacific expression may exert an even stronger control on tropical variability (*L. Wu*).

There was also discussion on a new flavor of a non-canonical ENSO characterized by a central Pacific warming (CPW) pattern which drives a teleconnection to the North Pacific that affects the variability of the NPO/NPGO (*E. Di Lorenzo*). This link may provide a positive feedback between tropics and extra-tropics.



Further understanding and quantifying of these coupling dynamics is necessary to establish the physical basis for exploring the predictability of North Pacific climate.

North Pacific western boundary variability and feedbacks
(Invited speakers: B. Qiu, M. Nonaka and B. Taguchi)

In this section we discussed how the large-scale modes of North Pacific variability (*e.g.*, PDO and NPGO) have a significant delayed impact on the low-frequency dynamics of the North Pacific western boundary, and explored mechanisms by which the western boundary SST variability can feed back onto large-scale atmospheric variability. The two dominant modes of oceanic variability in the Kuroshio-Oyashio Extension (KOE) region were viewed in terms of a lagged response to large-scale atmospheric variability of the AL/PDO and NPO/NPGO, respectively. Satellite SSH and SST analyses show that the first dominant mode in the KOE, which corresponds to a change in mean location of the jet's axis and a switch between a stable and unstable state (*B. Qiu*), is forced by the arrival of Rossby waves excited by the AL/PDO in the central North Pacific. From long-term *in situ* observations, the second mode of the KOE corresponding to an acceleration of the jet forced by the NPO/NPGO was reconstructed (*S. Minobe*). Effects of the NPO/NPGO modes were also reported in regional seas (*e.g.*, Okhotsk Sea, *E. Ustinova*). In addition, multi-decadal eddy-resolving ocean simulations elucidated some important non-linear dynamics and feedbacks in the KOE. It was shown that upon the arrival of these Rossby waves in the KOE region, adjustment of Kuroshio Extension's recirculation gyres organizes the incoming signals into narrow oceanic frontal zones, causing low-frequency variability in SST and surface heat fluxes (SHF), with large amplitudes along the fronts (*M. Nonaka*). The differential SHF across the oceanic fronts can potentially force the overlying atmosphere on a large scale. This feedback was investigated using atmospheric regional model experiments (*B. Taguchi*) that confirmed the importance of the near-surface air–sea temperature gradients in shaping the seasonal (winter–spring) mean atmospheric storm-track along the oceanic frontal zones, as observed. A more direct coupling *via* atmospheric Ekman pumping was also suggested as a key process to couple the ocean mesoscale and atmospheric circulation in the KOE (*N. Schneider*).

It has been shown that there is predictability with a lead-time of several years associated with the propagation and arrival of the Rossby waves excited by the AL and NPO. If air–sea feedbacks from the KOE SST to the large-scale atmosphere are confirmed, they may provide an alternative pathway to self-sustained modes of variability in the extra-tropics, which could enhance even more the predictability of North Pacific decadal climate.

Discussion and synthesis
(Coordinators: A. Miller, S. Minobe and E. Di Lorenzo)

The discussion section was opened with an attempt to summarize our current understanding of the Pacific climate dynamics and the linkages among the various modes of ocean and atmospheric variability, including the connections between tropics and extra-tropics. The schematic above (from *E. Di Lorenzo*) depicts a synthesis of the hypothesis and dynamics discussed during the workshop. In this schematic there are two sets of dominant dynamics in the Pacific: the ENSO/AL/PDO (red path) and CPW/NPO/NPGO (blue path). These are physically linked and connected through the ENSO system in the tropics. Both the PDO and NPGO are to first order the oceanic expressions of the atmospheric forcing associated with the AL and NPO variability, respectively, and therefore, integrate the low-frequency variations of the canonical and non-canonical ENSO through atmospheric teleconnections from ENSO→AL→PDO and CPW→NPO→NPGO. In addition to the tropics driving the extra-tropical variability, a link also exists from the extra-tropics back to the tropics through the NPO→CPW/ENSO (*D. Vimont, M. Alexander*), giving rise to the potential for a feedback between tropics and extra-tropics along the path NPO→CPW→NPO (*E. Di Lorenzo*). A link from the PDO to the tropics has also been suggested (*L. Wu*) but the relationship to the ENSO system is still being investigated.

While the AL and NPO atmospheric variability have maximum loading in the central and eastern North Pacific, their forcing also drives prominent decadal variations in the western North Pacific. Specifically, the oceanic adjustment to the SSHa anomalies of the AL/PDO and NPO/NPGO radiate Rossby waves that propagate into the western boundary. The arrival of the AL/PDO SSHa is associated with changes in the axis of the KOE, while the arrival of the NPO/NPGO SSHa modulates variations in the speed of the KOE. These two modes of KOE variability – the KOE Meridional Mode (shift in axis) and the KOE Zonal Mode (change in speed) – have been shown to capture the first two dominant modes of variability in the KOE. In the KOE, the expression of these modes is characterized by frontal scale features in SST and SHF that may feedback onto the modes of atmospheric variability (*e.g*., AL, NPO) (*M. Nonaka, B. Taguchi, N. Schneider*).

The discussion section emphasized the need to develop quantitative approaches to evaluate the role of these ocean/atmosphere modes, especially the more recently recognized CPW/NPO/NPGO system, in explaining North Pacific (SST, circulation), sea ice, climate over land and marine ecosystem indices. PICES provides an ideal opportunity to use such quantitative models with long-term observations in the North Pacific from Canada, China, Japan, Korea, Russia, and the United States of America.

We thank PICES and the Korean government for providing a great venue for the workshop. We thank the attendees and participants and, in particular, we appreciate the effort of many of the invited speakers who are new to the PICES community and who endured a long travel to contribute to the workshop. The organizers would also like to thank Alex Bychkov (PICES Executive Secretary) and Julia Yavzenko (PICES Database and Web Administrator) for helping with the organization and logistics, and a special thanks to James Overland (PMEL, NOAA, U.S.A.) who was one of the proposers and a strong supporter of this workshop.

Group photo of the workshop participants (workshop convenors and authors of this article, Manu and Shoshiro, are at the far right). A full-size version of this and other photos are available at http://www.sci.hokudai.ac.jp/~minobe/meeting/2009_PICES_WS8. (Courtesy of N. Schneider who took the picture and is absent in the photo!)

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Dr. Shoshiro Minobe (minobe@mail.sci.hokudai.ac.jp) is a Professor at the Graduate School of Sciences, Hokkaido University, Japan. His research interests focus on decadal climate variability and air–sea interaction. Included in his publications is a widely-referenced article proposing 50-yr climate variability and an interpretation of climate regime shifts associated with 50-yr and 20-yr climate variability. His paper on the ocean-to-atmosphere influence over the Gulf Stream was featured as the cover article of the journal Nature in 2008. Shoshiro worked as a convenor for the PICES symposium and workshops (1999, 2006, 2007) for decadal climate variability and its relation to marine ecosystem, and as a guest editor of the Progress in Oceanography special issue on "North Pacific Climate Regime Shift" (2000). He also served as a member of the Implementation Plan Writing Team for the PICES scientific program, FUTURE.

Continued from inside back cover

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Continued on inside back page

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The North Pacific Marine Science Organization (PICES) was established by an international convention in 1992 to promote international cooperative research efforts to solve key scientific problems in the North Pacific Ocean.

PICES regularly publishes various types of general, scientific, and technical information in the following publications:

PICES ANNUAL REPORTS – are major products of PICES Annual Meetings which document the administrative and scientific activities of the Organization, and its formal decisions, by calendar year.

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Front cover figure

Two examples of member activities applied to Working Group 20’s first and third terms of reference: i) to analyse and evaluate climate change projections for the North Pacific and its marginal seas based on predictions from the latest global and regional models submitted to the Intergovernmental Panel on Climate Change for their 4th Assessment Report, and iii) to facilitate the development of higher-resolution regional ocean and coupled atmosphere-ocean models that are forced by, and take their boundary conditions from, IPCC global or regional models. Top: A regional ecosystem model version of COCO-NEMURO applied to the lower trophic level marine ecosystem simulating the timing of maximum chlorophyll concentration (dark blue is January, red is June) in the spring bloom in the Kuroshio-Oyashio system. (See Yamanaka *et al*. for more details.) Bottom: A Northeast Pacific regional climate model nested in the CCSM global climate model relative to the CCSM model showing sea surface temperature (dark blue is –3.0°C and red is +3.0°) and wind anomalies (maximum is approximately 1.5 m/s) in August. (See Curchitser *et al*. for more details.)